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A review of safety issues in lithium-ion battery transportation process: Research advances and challenges

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ABSTRACT

The growing demand for lithium-ion battery transportation, coupled with inadequate regulatory frameworks, has led to frequent fire incidents during transit, resulting in substantial losses of life and property. These recurring accidents underscore the urgent need to enhance the safety of lithium-ion batteries throughout the transportation process. This review begins by identifying key factors affecting battery safety during transport, such as mechanical abuse, thermal abuse, air pressure variations, and salt concentration. It then synthesizes current technological advancements and real-world battery transportation scenarios to conduct a targeted analysis of the critical technical challenges constraining transportation safety limits—specifically, ventilation and heat dissipation strategies, thermal monitoring, and fire safety design—while systematically examining the limitations of existing research. Accordingly, the paper proposes actionable recommendations and technical measures to improve the safety of lithium-ion battery transportation. Additionally, it outlines existing international standards and testing protocols governing lithium-ion battery transport and highlights shortcomings in the current regulatory landscape. The insights presented herein could provide valuable guidance for optimizing safety protocols in the transportation of lithium-ion batteries.

1. Introduction

The global energy crisis and accelerating climate change have driven a transition from fossil fuels to renewable energy sources (Hu et al., 2022). Over the past decade, lithium-ion batteries (LIBs) have been widely adopted in consumer electronics, electric vehicles, and large-scale energy storage systems owing to their superior properties, including high energy density, long cycle life, absence of memory effects, and low self-discharge rates (Huang et al., 2025b; Meng et al., 2023a). Statistics from EVTank indicate that, compared with 2022, the total global shipments of LIBs increased by 25.6 %–1202.6 GWh in 2023, and shipments are projected to reach 5000 GWh by 2030 (Xu and Liu, 2025). However, in recent years, safety accidents during the transportation of LIBs have occurred frequently, posing severe threats to property and human safety. Fig. 1 presents a schematic diagram of battery transportation and representative recent fire incidents reported during transport, including a 2019 fire involving a wooden pallet loaded with LIBs at Hong Kong International Airport; a 2024 incident in which a semi-trailer truck transporting large-format LIBs caught fire on Highway 47 near the Port of Los Angeles; and a 2024 smoke-and-fire event involving a container carrying approximately 15 tons of lithium batteries at the Port of Montreal, Canada. Table 1 shows partial global LIB transportation accidents from 2019 to 2025. These accidents have caused substantial property losses and exposed critical challenges in the safe transportation of LIBs, thereby highlighting the urgency of addressing this issue.

The primary modes of transportation for power LIBs encompass road, air, maritime, and railway transport (Huo et al., 2017). According to the "Industry Development Report on Power Battery Transportation in 2023", road transportation currently represents the dominant mode for power battery logistics in China, accounting for approximately 90 % (Cover News, 2024). In practical transportation scenarios, LIB packages

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typically adopt high-density stacking configurations (Cheng et al., 2020). This practice aims to maximize space utilization and enhance transportation efficiency, but it also elevates safety risks. When a single battery undergoes thermal runaway (TR) triggered by an internal short circuit, external impact, or other initiating events, the released heat can rapidly propagate to adjacent batteries through conduction, radiation, and convection (Mishra et al., 2021), thereby inducing cascading thermal runaway that may ultimately manifest as battery fire or explosion (Huang et al., 2025b). Additionally, the smoke generated during LIB TR not only has high thermal energy but also contains flammable and toxic components (Liu et al., 2023; Peng et al., 2020). Due to the enclosed and limited space of transportation vehicles/containers, the accumulation of such smoke can readily reach flammable (explosive) limits, leading to secondary explosions. Moreover, toxic smoke may cause acute poisoning, injuries, or even fatalities among personnel (Wang et al., 2025b).

To address the aforementioned safety challenges, this study systematically analyzes the key issues related to the safe transportation of power LIBs, with the following structure: First, it provides a detailed analysis of the core components, classification, and operating principles of LIBs. Second, it analyzes the primary transportation risk factors (mechanical abuse, thermal abuse, air pressure, and salt concentration). Third, it systematically reviews the research progress of ventilation and heat dissipation strategies, thermal monitoring, and fire safety design in the context of LIB transportation, clearly delineates the limitations of current research, and further proposes targeted improvement strategies and potential future research directions. Finally, it introduces the LIB transportation specification standards and test requirements, focuses on evaluating discrepancies and limitations between international and national standards, and puts forward corresponding prospects for future development. This study is expected to provide a concise and comprehensive reference for scholars and industry practitioners in related fields, and further inspire the development of safer LIB products, more reliable monitoring and early warning systems, and more efficient fire-extinguishing agents, ultimately contributing to the enhancement of overall safety levels in LIB transportation.

2. Overview of LIBs

LIBs are mainly composed of four core components: cathode, anode, separator and electrolyte (Talele et al., 2024). These components collectively determine the battery's electrochemical performance and stability. Among them the anode material of the battery is usually graphite. According to the different materials of the cathode, the batteries can be categorized into lithium nickel manganese cobalt oxide (NCM) ternary battery, lithium nickel cobalt aluminum (NCA) ternary battery, lithium iron phosphate (LFP) battery, lithium cobalt oxide (LCO) battery, etc. (Bhoir et al., 2025). At present, NCM and LFP batteries account for more than 90 % of global battery production, and their share continues to rise in response to growing demand from electronic devices and new energy vehicles (Ning et al., 2024). With the pursuit of high energy density of battery, the ternary battery is being developed toward higher nickel and lower cobalt (Feng et al., 2018). Meanwhile, LFP batteries have been widely used in both energy storage power plants and new energy vehicles, primarily due to their recognized high safety performance (Zhou et al., 2023). The separator and electrolyte are two other critical components of LIBs. The separator of an LIB serves to physically isolate the cathode and anode, thereby preventing internal short circuits. The electrolyte is mainly composed of organic solvents, lithium salts, and necessary additives, and its core function is to conduct lithium ions between the cathode and anode.

As shown in Fig. 2, power LIBs can also be classified by shape into cylindrical, prismatic, and pouch types. Both cylindrical and prismatic batteries are manufactured by winding internal materials into coils, with their outer casings typically made of steel or aluminum. In contrast, pouch batteries are constructed by stacking layered materials and are encapsulated using aluminum-plastic composite film packaging.

The working principle of an LIB is based on the intercalation and deintercalation of lithium ions between the cathode and anode. During charging, lithium ions migrate from the cathode, diffuse through the electrolyte, traverse the separator, and are ultimately intercalated into the anode (typically layered graphite). At the same time, to maintain electrical neutrality, the electrons flow in the opposite direction through an external circuit. When the battery is discharging, as shown in Fig. 3, the external circuit of the electrons will flow from the anode to the cathode, and lithium ions inside the battery deintercalated from the graphite and return to the cathode. Taking widely used NCM and LFP batteries as representative examples, their electrode reactions during charge and discharge are summarized in Table 2. The charging and discharging processes of Li-ion batteries is also always accompanied by a

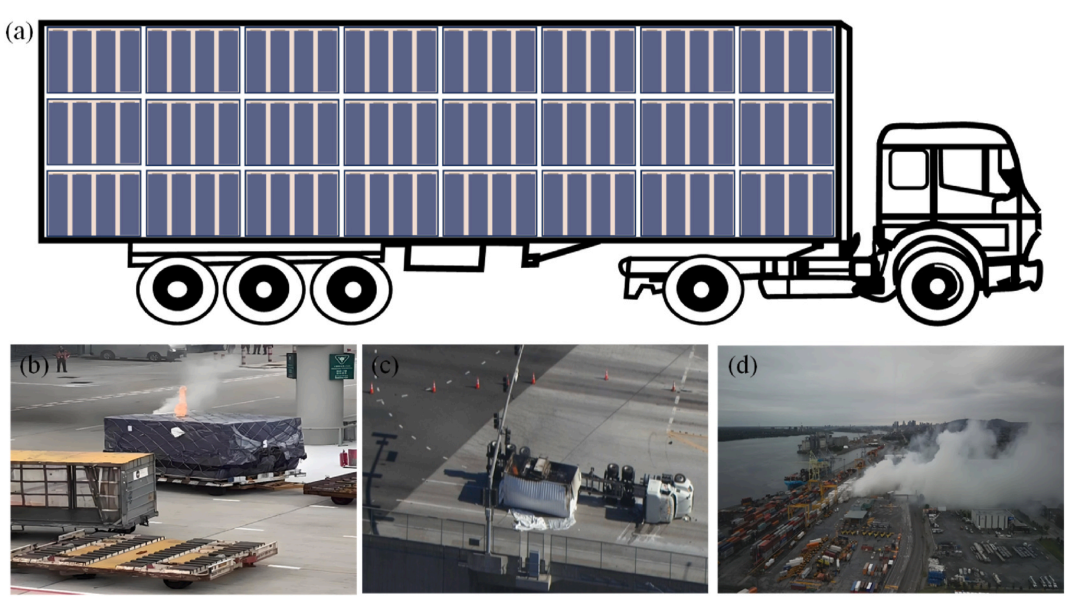


Fig. 1. Schematic diagram of battery transportation and fire incidents in the transportation of LIBs in recent years: (a) Schematic diagram of battery transportation; (b) The fire accident of a wooden pallet loaded with LIBs in Hong Kong airport (Air Cargo World, 2019); (c) The combustion fire of a truck carrying large LIBs on highway (CBS News, 2024); (d) The smoke and fire incident involving a container carrying 15 tons of lithium batteries at the Port of Montreal (Global News, 2024).

certain amount of Joule heat generation (Chen et al., 2021); therefore it is necessary to ensure an effective heat dissipation path to maintain the battery's safe and stable operation (Shen et al., 2025). Before transportation, batteries are typically charged to a certain level to maintain their condition and performance. For example, LIBs should not exceed 30 % SOC of their nominal capacities when shipped via air (Xu and Liu, 2025). This indicates that lithium-ion batteries still store a non-negligible amount of energy during transportation, which inherently increases safety risk.

3. Hazardous factors during LIB transportation

TR is a critical safety hazard in LIBs, serving as a primary cause of battery fires or explosions (Hou et al., 2025). This phenomenon occurs when the internal heat generation exceeds the heat dissipation capacity, leading to the irreversible thermal decomposition of a battery's constituent materials (Zhao et al., 2025; Venturelli et al., 2025). Fig. 4 illustrates a typical TR process for prismatic LIBs equipped with a safety valve, including gas generation, vent opening, and possible jet-flame formation. In contrast, pouch cells lack dedicated venting mechanisms, their TR behavior differs and usually involves swelling and laminate rupture rather than directional venting.

The three major triggers of TR in Li-ion batteries are usually considered as mechanical abuse, thermal abuse, and electrical abuse (Chen et al., 2019a; Wang et al., 2025a; Nie et al., 2024; Xiao et al., 2023). However, in transportation scenarios, electrical abuse is typically negligible due to the batteries being in an open-circuit state, as illustrated in Fig. 5. In cases of mechanical abuse, external forces cause battery deformation, generating internal stresses. If these stresses accumulate to a critical level, they may tear the separator—resulting in direct or indirect contact between the cathode and anode, i.e., an internal short circuit. The heat generated by the internal short circuit accelerates separator degradation and initiates a series of exothermic reactions within the cell materials. If these reactions continue without effective heat dissipation, the resulting temperature rise can ultimately lead to TR or even explosion (Liu et al., 2020a). Notably, when an LIB is at a high SOC, the stored electrochemical energy and the number of reactive species increase substantially, thereby significantly elevating

Table 1
Partial global LIB transportation accidents from 2019 to 2025.

Time	Transportation mode	Country/region	Location	Description	Consequences
2025.08.08	Road	India (Odisha)	NH-16 near Chhatrapur	Container carrying EVs caught fire; short-circuit suspected.	Total cargo loss; road disruption
2025.05.29	Road	China (Jiangsu)	The Taihu Lake Street, Wuzhong District	Cargo PACKs ignited in transit; firefighters used berm-and-immersion tactic	cargo loss
2025.05.23	Road	China (Guizhou)	Shanghai-Kunming Expressway	A truck carrying 33 tons of waste batteries caught fire.	Traffic disruption; cargo loss
2025.04.17	Road	China (Suzhou)	Taicang City	A logistics company's transport vehicle carrying 8 LIBs caught fire accidently	cargo loss
2025.01.07	Road	Italy (Veneto)	A4 motorway, Sommacampagna	Truck fire on motorway	Traffic disruption; cargo loss
2025.01.06	Road	China (Taiwan)	Yunlin Huwei Interchange	Container truck with batteries overturns/ rolls over	Traffic disruption; cargo loss
2024.12.01	Road	France (Doubs)	Montbéliard, Stellantis plant	Fire in trailer at factory gate	cargo loss
2024.09.26	Road	USA (California)	Near Highway 47	Semi-truck overturned; cargo of LIBs damaged; intense fire and intermittent explosions	Multi-day fire; closure of bridge and nearby roads; cargo loss
2024.09.25	Road	United Kingdom (London)	Hammersmith and Fulham	Explosion during compaction; fire service attributed to batteries/aerosols in bin	Truck damaged
2024.09.23	Sea	Canada (Quebec)	Port of Montreal	Container fire; evacuations and shelter-in-place advisories issued nearby	Dock operations affected
2024.09.17	Road	USA (Nevada)	Highway 95	A collision between a truck carrying wood and one transporting battery caused the latter to catch fire and burn	Traffic disruption; cargo loss
2024.09.09	Road	Australia (New South Wales)	Pacific Highway, south of Kempsey	Semi-trailer fully involved; prolonged hazmat firefight; multiple reignitions	Highway closure; cargo destroyed.
2024.08.12	Road	Colombia (Cundinamarca)	Autopista Sur, Soacha	Truck exploded and burned on highway near gas station	Traffic disruption; cargo loss
2024.06.27	Road	China (Hefei)	Hefei Service Area, G5011 Expressway	Truck fire at highway service area destroyed cargo	¥501 000 loss
2024.07.26	Road	USA (California)	Interstate 15	A truck transporting six large LIBs caught fire on Interstate 15	Shut down Interstate 15 for 43 h
2024.01.25	Road	China (Hubei)	1575 + 700 m on the Xiangyang-Yicheng direction of Erlianhaote Guangzhou (G55)	A truck carrying 20 tons of battery packs suddenly caught fire	Traffic disruption; cargo loss
2023.07.18	Road	China (Hubei)	Shangang Section on the 4th Ring Road, Dongxihu District	A truck carrying battery packs suddenly caught fire	cargo loss
2023.05.13	Road	China (Wuhan)	Shazhou Yangtze River Bridge	A semi-trailer truck loaded with waste batteries caught fire in the middle of the bridge	Traffic disruption; cargo loss
2022.06.11	Road	China (Guangdong)	Hengling Service Area	A truck carrying nearly 30 tons of lithium-ion power system battery packs caught fire accidently	cargo loss
2022.03.04	Sea	USA (California)	San Pedro Bay, Los Angeles/Long Beach Ports	A fire broke out in the LIB containers waiting to be loaded at the WBCT terminal.	cargo loss
2022.01.12	Road	China (Wuhan)	Jinggang'ao Expressway	Jinggang'ao Expressway	Traffic disruption; cargo loss
2021.08.17	Road	China (Hubei)	Jinggang'ao Expressway (G4) Xiaochang Section, Hubei Province	A truck carrying batteries caught fire accidently	Traffic disruption; cargo loss
2020.01.04	Sea	–	During the voyage from Port Klang to Nhava Sheva Port in India	A very large container ship carrying LIBs caught fire suddenly during transportation.	Cargo damage and vessel schedule delay
2019.01.08	Air	China (Hong Kong)	Hong Kong airport	LIBs caught fire at Hong Kong International Airport	cargo loss

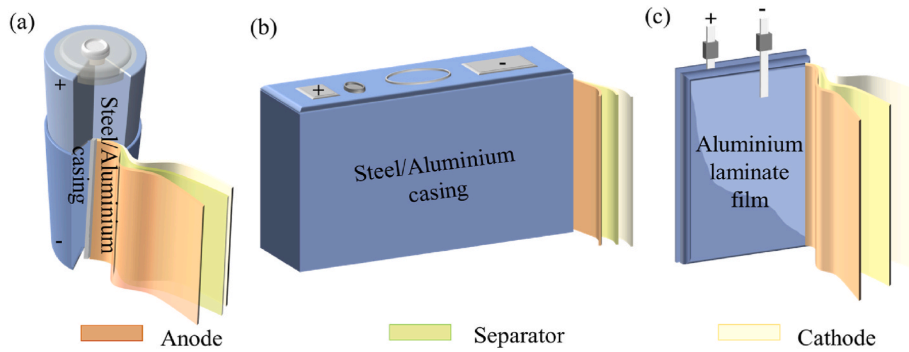


Fig. 2. Different shapes of power LIBs: (a) cylindrical; (b) prismatic; (c) pouch.

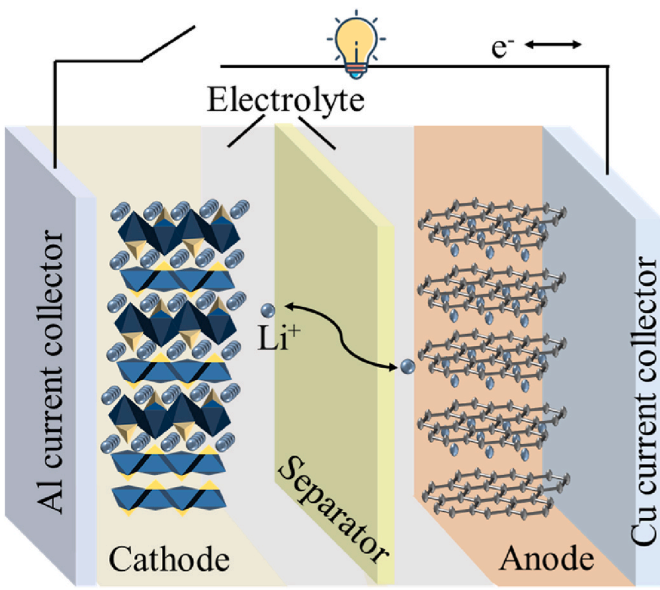


Fig. 3. Schematic diagram of working principles of LIBs during discharging.

Table 2
Electrode reactions of NCM and LFP batteries during charging and discharging.

Battery type	Reaction	
NCM battery	Cathode	$LiNi_xCo_yMn_zO \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_{1-n}Ni_xCo_yMn_zO + nLi^+ + ne^-$
	Anode	$nLi^+ + mC + ne^- \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_nC_m$
	Full cell	$LiNi_xCo_yMn_zO + mC \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_{1-n}Ni_xCo_yMn_zO + Li_nC_m$
LFP battery	Cathode	$LiFePO_4 \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_{1-x}FePO_4 + xLi^+ + xe^-$
	Anode	$mC + xLi^+ + xe^- \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_xC_m$
	Full cell	$LiFePO_4 + mC \underset{discharging}{\overset{charging}{\rightleftarrows}} Li_{1-x}FePO_4 + Li_xC_m$

the likelihood and severity of combustion during the aforementioned processes (Liu et al., 2025a). In thermal abuse scenarios, the battery surface and transfers to the battery interior, causing the separator to melt and releasing heat during a short circuit. Moreover, once the internal temperature reaches the decomposition threshold of the battery's components, exothermic chemical reactions are initiated, further elevating the risk of TR (Ren et al., 2021). Notably, in high-altitude areas, the combined effects of wide temperature ranges and low atmospheric pressure can accelerate battery aging and significantly degrade safety performance compared to low-altitude environments (Xie et al., 2025). Based on the above analysis, the following sections (3.1–3.3) will provide a detailed elaboration on the common abuse modes encountered during the transportation of LIBs.

3.1. Mechanical abuse

LIBs are inherently susceptible to mechanical abuse across diverse transportation scenarios. For instance, in maritime, air, road, and railway transport, vibrations from vessels, aircraft, vehicles or train—exacerbated by improperly secured pallets—may induce accidental LIB drops. Additionally, road transport is characterized by a higher incidence of traffic accidents, where collisions or impact can lead to battery crushing. These examples illustrate typical scenarios of mechanical abuse that LIBs may encounter during transport.

3.1.1. Penetration

Penetration risk arises when LIBs contact sharp/rigid objects in transit. In maritime transport, rough sea-induced cargo displacement may drive metallic fasteners (e.g., loose bolts) or sharp edges into adjacent batteries. For air transport, constrained cargo hold space and rapid maneuvers (e.g., sudden ascent/descent) can cause LIB collisions with exposed pallet nails or rigid frames. In road and railway transport, emergency braking or transit collisions may force batteries against metallic protrusions (e.g., truck chassis bolts) or fragmented cargo (e.g., broken pallets), thereby piercing the battery casing. Such penetration events can directly breach the battery casing and induce internal short circuits without external heat input, making penetration a key scenario for simulating transport-related battery failure (Qi et al., 2021). When a penetrating tool (e.g., a needle) pierces a LIB, materials in different battery layers come into contact, forming four typical internal short-circuit modes: anode-cathode, anode-collector, cathode-collector, and collector-collector (Liu et al., 2020a). Among these, the anode-collector mode poses the greatest danger, followed by the anode-cathode mode (Santhanagopalan et al., 2009) as shown in Fig. 6.

Mao et al. (2018) proposed the concepts of "micro-short-circuit unit" and "string of candied haws" structure, which effectively explain the short-circuit mechanism and heat generation process of cylindrical LIBs during penetration, as illustrated in Fig. 7. Maleki and Howard (2009) further studied the heat and current generation mechanisms of LIBs under penetration, finding that approximately 70 % of the battery energy is released in the central region within 60 s, resulting in a sharp temperature rise. They also noted that short circuits initiated near the electrode edge can lead to a faster initial temperature rise, as local heat dissipation is more restricted. Zavalis et al. (2012) developed a 2D model of square LIB pinning via COMSOL Multiphysics, identifying that Li-ion mass transfer in the electrolyte is critical to peak current (and thus maximum temperature rise). They also noted two current pathways (through the nail and electrode), with the latter accounting for about 75 % of total current.

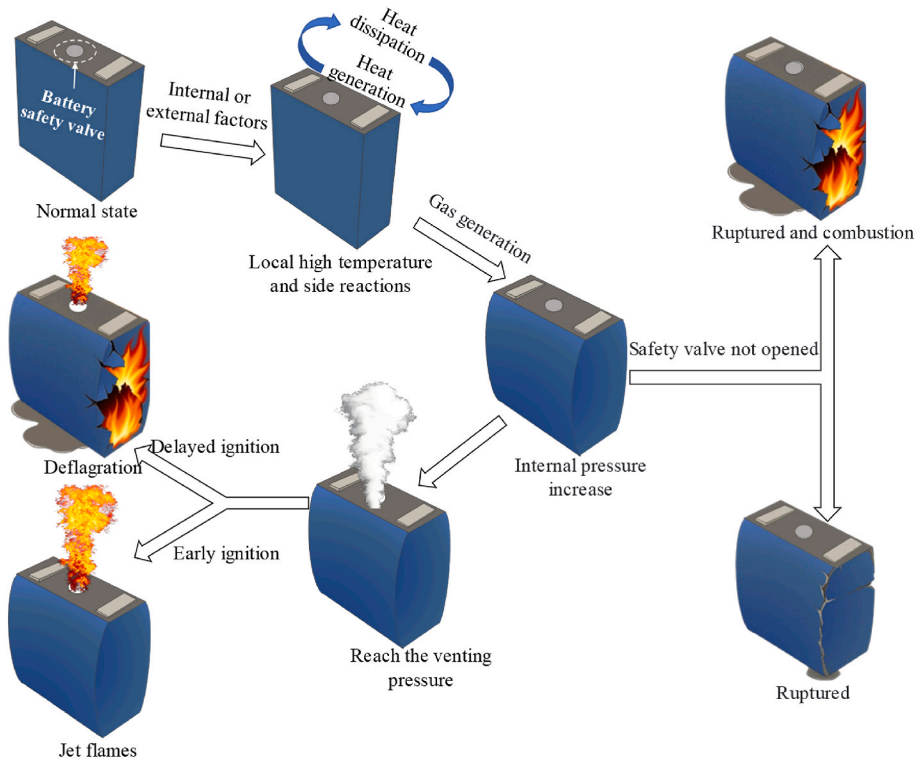


Fig. 4. Battery TR process.

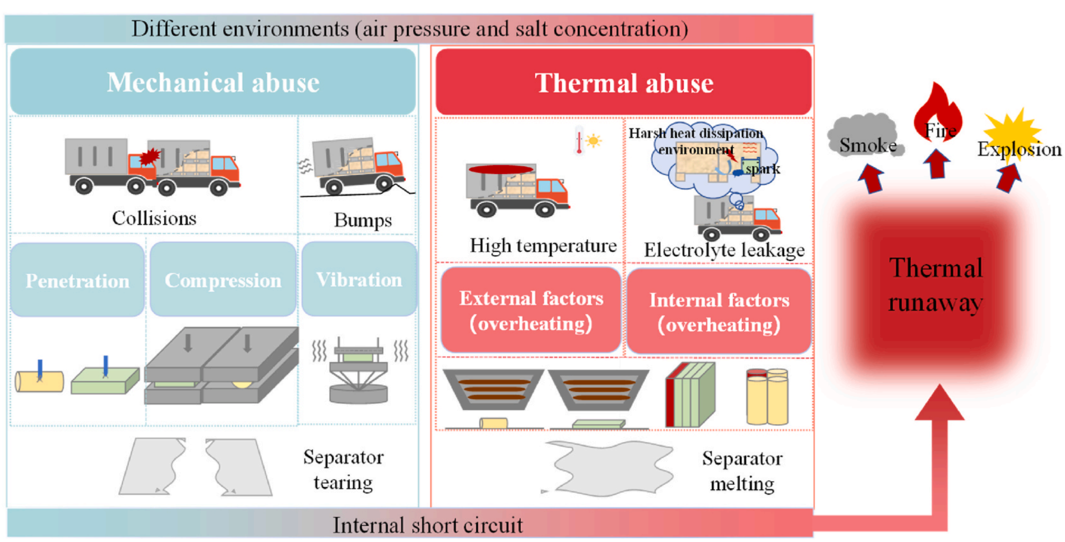


Fig. 5. Hazardous factors of LIBs in road transport scenarios.

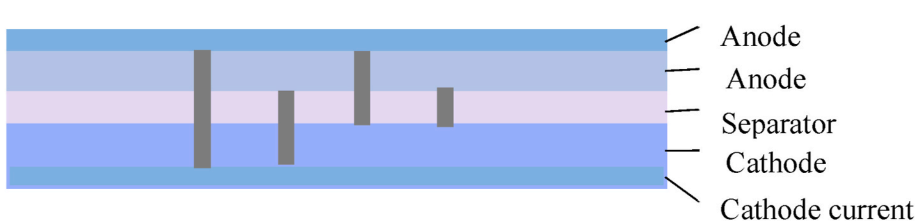


Fig. 6. Four types of internal short circuit modes.

Several factors influence the TR of Li-ion batteries under pinning conditions. Mao et al. (2018) varied the battery charge state, pinning position, depth and speed to assess their effects. They reported that penetration at the center of the battery leads to a more pronounced TR

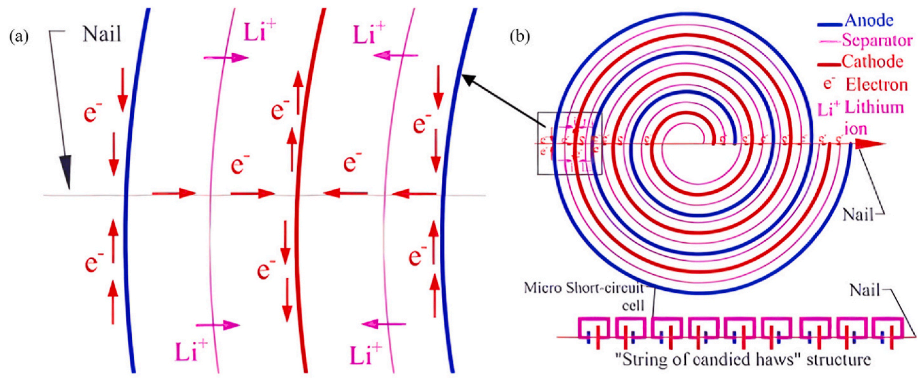


Fig. 7. Schematic diagram of internal short circuit induced by penetration for cylindrical LIBs (Mao et al., 2018): (a) the enlargement of micro short-circuit cells. Arrows show flow directions of Li ions and electrons; (b) the jelly-roll penetrated by a nail and "string of candied haws" structure.

response because multiple electrode layers are disrupted simultaneously, enabling faster propagation of TR, while battery temperature correlates poorly with penetration depth. As the state of charge and penetration speed increase, the temperature distribution becomes more uneven. If the temperature exceeds 233 °C, all batteries will fall into TR due to the contraction of the separator and the triggering of the reaction between the anode and the cathode. Chen et al. (2019c) emphasized that the electrical contact resistance at the nail–electrode interface governs the magnitude of the short-circuit current. In contrast, Li et al. (2023a) analyzed the short-circuit resistance within the damaged electrode layers, showing that failure area and electrode contact conductivity jointly influence the resulting short-circuit behavior. Ren et al. (2024) conducted numerical simulations and demonstrated that the severity of penetration-induced TR at the cell level increases with higher SOC, a larger penetration radius, and a lower penetration speed. Liu et al. (2025b) reported that although penetration-initiated TR in the target cell, no TR propagation was observed to adjacent cells across all three tested spacing configurations. The temperature of neighboring cells remained below 50 °C and rapidly stabilized, suggesting that the heat released from the failed cell was insufficient to trigger secondary thermal failures.

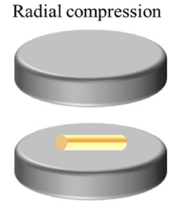
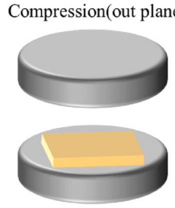
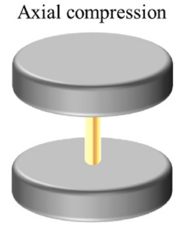
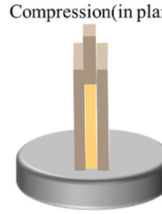
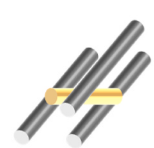
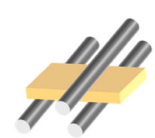
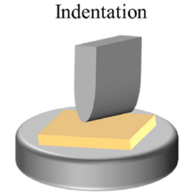
However, existing penetration studies have primarily focused on single LIBs (with different cathode materials or shapes). The behavior of TR propagation in densely packed batteries—a common configuration in transportation, especially in confined spaces—has not yet been sufficiently characterized. This highlights the need for more targeted investigations: specifically, TR experiments on battery packs should be designed to reflect realistic transportation scenarios, enabling direct observation of propagation characteristics and transient temperature evolution at the pack level under transport-specific conditions. Such experimental efforts can provide a robust empirical basis for addressing the identified research gaps and for developing effective prevention and mitigation strategies for TR during LIB transportation.

3.1.2. Compression

During LIB transportation, external compression from transport-related hazards (e.g., over-stacking, cargo shifts, collisions) can deform battery casings and damage internal components, thereby triggering flammable electrolyte leakage and increasing the risk of fire or explosion. Therefore, the study of the response behavior of battery constituent materials under mechanical loads is fundamental to understanding the mechanical integrity of LIBs. Previous studies have extensively investigated the mechanical properties of these components under various loads (Amiri et al., 2016; Hahn et al., 2025; Lai et al., 2014b; Li et al., 2024a; Zhu et al., 2018) and explained their failure mechanisms via multi-directional loading experiments (Perea et al., 2018).

Subsequently, researchers have shifted their focus to the battery level, employing various extrusion loading methods (Arief Budiman et al., 2022; Lai et al., 2014a; Keshavarzi et al., 2022; Xu et al., 2016; Voyiadjis and Akbari, 2023; Zhu et al., 2016) for different shapes of batteries to investigate their mechanical failure characteristics and TR characteristics (Sahraei et al., 2014; Zhu et al., 2022) of different types of batteries under varying mechanical loading positions and indenter shapes, as shown in Table 3. Sahraei et al. (2014) tested small consumer battery packs with different indenters, finding that short circuits are associated with local force peaks, voltage drops, and temperature rises, and that the indenter head radius is linearly correlated with the force required to trigger a short circuit. Similarly, Zhu et al. (2022) conducted quasistatic loading tests on square LIBs with three indenters, measuring force and displacement while recording voltage drops to monitor the

Table 3
Schematic diagram of different compression scenarios.

Cylindrical battery	Ref.	Prismatic battery	Ref.
Radial compression 	Xu et al. (2016)	Compression(out plane) 	Lai et al. (2014a) Lai et al. (2014b)
Axial compression 	Zhu et al. (2016)	Compression(in plane) 	Lai et al. (2014a) Lai et al. (2014b)
Three-point bending 	Arief Budiman et al. (2022)	Three-point bending 	Keshavarzi et al. (2022)
Indentation 	Voyiadjis and Akbari (2023)	Indentation 	Zhu et al. (2022)

short-circuit conditions. Based on these experimental results, they developed a finite element model to simulate the failure behavior of the battery under different types of indentation heads.

Extrusion-induced TR in batteries is primarily attributed to the occurrence of internal short circuits, making it critical to predict these short circuits based on the model. The evolution of modelling approaches has progressed from the initial simple mechanical models (Sahraei et al., 2014) to more sophisticated mechanical-electrochemical-thermal coupling models (Wang et al., 2023b). These advanced models offer a more comprehensive understanding of the electrical and thermal responses within the battery during an internal short circuit, enhancing the accuracy of predictions.

At the module level, Hu et al. (2020)demonstrated that the mechanical response of multiple batteries stacked under compression differs significantly from that of a single battery. This difference is characterized by uneven deformation within each battery, where neighboring batteries in adjacent rows compress against each other, potentially creating vulnerable regions and increasing the risk of failure. This is particularly relevant for transportation, where LIBs are often stacked horizontally and vertically. Future research should prioritize two key directions: the development of in-situ diagnostic techniques capable of visualizing internal deformation within batteries, and the establishment of multi-physics models to predict fire and explosion risks under compression conditions representative of real transportation scenarios.

3.1.3. Vibration

Across maritime, air, road and railway transportation of LIBs, continuous vibrations inherent to each Transportation mode—such as those from ocean waves (maritime), aircraft engine operation (air), uneven road surfaces (road), and train traction system oscillation (railway)—subject the batteries to cyclic mechanical stresses and repeated impacts. Studies have indicated that mechanical vibration has a negative effect on the internal mechanical structure and electrical properties of LIBs (Awan et al., 2025; Brand et al., 2015; Zhang et al., 2017). For example, specific vibration loads can deform or rupture electrode materials. However, the inconsistent vibration cycles and limited sample sizes in existing studies make it difficult to reach definitive conclusions about how vibration affects LIB electrical performance. Wang et al. (2024b) partially addressed this gap by evaluating battery electrochemical performance under different vibration frequencies. They found that pre-vibration leads to additional capacity loss during subsequent cycling and that the strongest degradation occurs at 50 Hz. The DC internal resistance after cycling also increases, with the largest rise again at 50 Hz, which suggests aggravated polarization and ohmic losses. As shown in Fig. 8, SEM images of electrodes from cells vibrated at 50 Hz and then cycled reveal obvious cathode particle breakage and a rougher graphite anode surface, consistent with loss of active material and deterioration of the electrode–electrolyte interface.

Regarding TR under vibration, Li et al. (2022a) experimentally investigated the effects of mechanical vibration frequency and amplitude on the charging and discharging performance and TR characteristics of 18 650-type LIBs under low-pressure conditions. They found that, compared with non-vibration batteries at atmospheric pressure, mechanical vibration under low pressure increased the TR temperature and significantly altered the safety-valve ejection time. They also observed that low-frequency vibration accelerated the onset of internal short circuits and led to a marked reduction in battery capacity, whereas high-frequency vibration caused a pronounced increase in gas concentration during TR. These findings show that vibration frequency and amplitude play a key role in shaping the TR behavior and electrochemical response of LIBs under low-pressure environments.

In summary, existing studies demonstrate that vibration can degrade the mechanical integrity and electrochemical performance of LIBs and can alter their TR behavior. However, the mechanisms by which vibration interacts with TR have not been fully explored. Future research should focus on large-scale experiments to construct a more comprehensive database, and integrate experimental results with multi-physics modeling to better understand the underlying mechanisms and predict TR behavior.

3.2. Thermal abuse

Thermal abuse in transported LIBs arises from both external and internal factors. Externally, high temperatures (e.g., summer heat) are a key driver; internally, substandard manufacturing can cause electrolyte leakage. The dense stacking of batteries during transportation can lead to poor heat dissipation conditions, which may cause localized temperatures to rise excessively and reach the ignition points of flammable electrolytes. Such circumstances may lead to the ignition of a localized

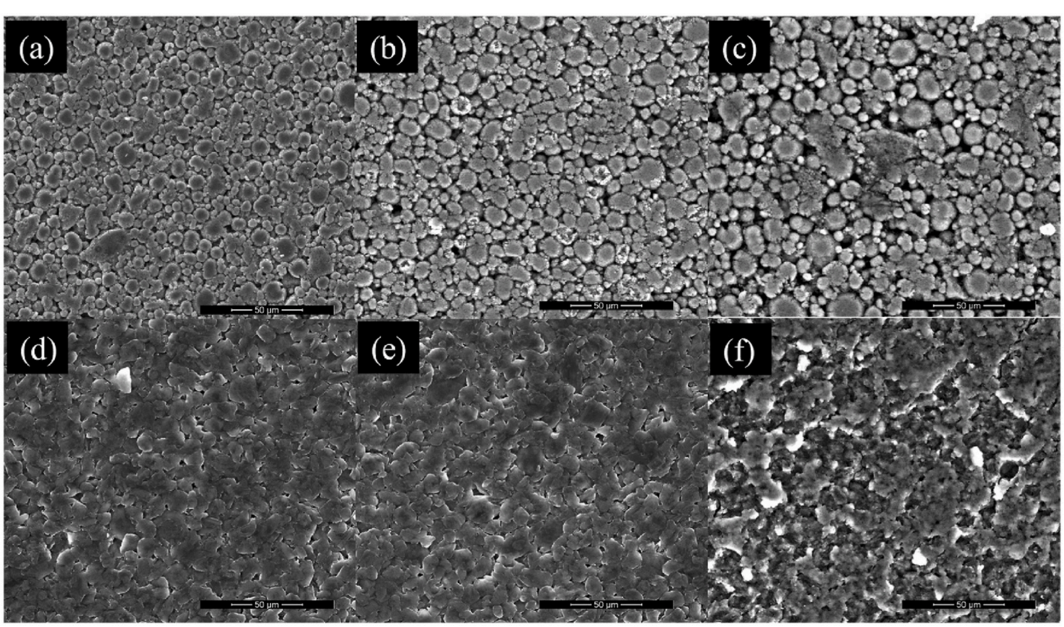


Fig. 8. SEM images of the battery: (a) Cathode of fresh battery; (b) Cathode of battery after vibration with 50 Hz; (c) Cathode of battery for 100 cycles after 50 Hz vibration; (d) Anode of fresh battery; (e) Anode of battery after vibration with 50 Hz; (f) Anode of battery for 100 cycles after 50 Hz vibration (Wang et al., 2024b).

fire, subsequently resulting in the TR of the batteries. Additionally, the narrow spacing between battery cells significantly exacerbates the propagation of TR (Zhang et al., 2026). In thermal abuse scenarios, overheating induces a series of exothermic side reactions: high-temperature capacity fading; SEI film decomposition; anode-electrolyte reaction; separator melting process; cathode decomposition reaction; electrolyte solution decomposition reaction; reaction between anode and binder; and electrolyte combustion (Feng et al., 2018; Wang et al., 2025c), as shown in Fig. 9. Notably, separator collapse causes large-scale internal short circuits, leading to instantaneous electrical energy release and TR, as shown in Fig. 10. Generated heat transfers to adjacent batteries, producing toxic, flammable fumes that risk explosion when exposed to flames.

The study of TR of Li-ion batteries under thermal abuse conditions has broadened in scope from examining individual batteries to considering module batteries. Zou et al. (Zou and Lu, 2023) experimentally explored the thermal hazards of ternary soft-packed batteries of varying capacities under different heat flux conditions. Their findings revealed that the peak heat release rate (HRR) of a 78 Ah battery and total heat release (THR) have low sensitivity to applied heat flux, which is contrary to the general conclusions previously drawn from studies on 18 650-type batteries. As depicted in Fig. 11, Zhang et al. (2022c) quantified the explosion limits of TR gases from LCO 18650 cells under different SOC conditions. The lower explosion limit shows the same trend as the change in alkane content, while the upper explosion limit shows the same trend as the unsaturated hydrocarbon content. The alkanes content changes with the trend of increasing first and then decreasing, while unsaturated hydrocarbons content shows a opposite trend. Notably, the explosion risk is minimized at 50 % SOC. As shown in Fig. 12, Zhang et al. (2022b) investigated the explosion limits of NCM811 batteries using gas composition analysis and innovative in-situ detection. They found that batteries at 30 % SOC release vent gas mixtures characterized by the narrowest explosion range and the lowest upper explosion limit. This implies that the vented gas is ignitable only within a highly restricted flammability range, thereby highlighting the suitability of this SOC for battery transportation and storage. Contrary to traditional perceptions, LFP batteries generate more hydrogen during TR (lower combustion limit, higher explosion hazard) (Wei et al., 2023). Wang et al. (2022) further conducted a comparative study on TR released gas hazards across five LIB types, finding that NCM811 batteries have the highest temperature/pressure rises, while LFP batteries release the most H_2 and C_2H_4. In terms of gas toxicity, for LFP batteries, the gas emitted before TR is not toxic (Jia et al., 2023). Nevertheless, ternary batteries release multiple toxic gases during TR, among which asphyxiating species (e.g., CO, HCN) exert pronounced effect than irritating species (e.g., HF, HCl). The toxicity of these emissions is assessed using standardized metrics: the fractional effective dose (FED) is employed to quantify the asphyxiating effects, whereas the fractional effective concentration (FEC) is used to evaluate the irritating impacts of specific pollutants. Furthermore, as the nickel content in ternary batteries increases, the overall toxicity of the released gases also rises, resulting in greater toxic hazards compared with those of LFP batteries (Liu et al., 2023).

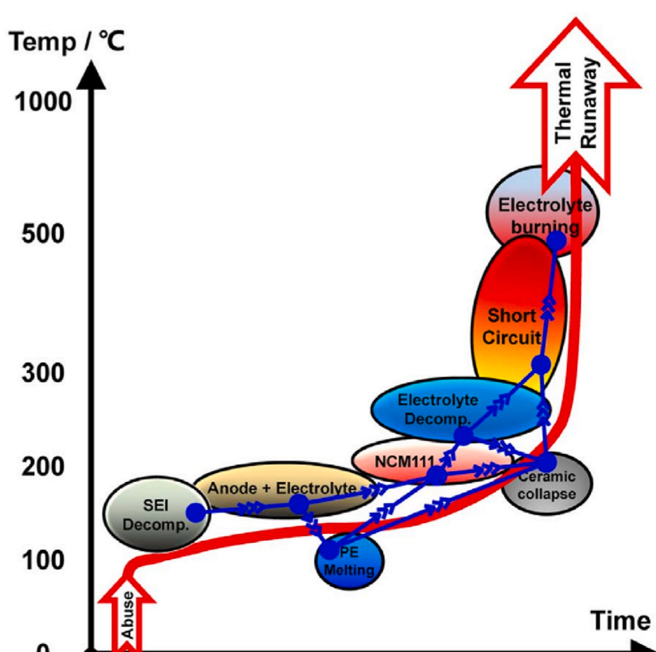


Fig. 9. Qualitative interpretation of the chain reactions during TR (Feng et al., 2018).

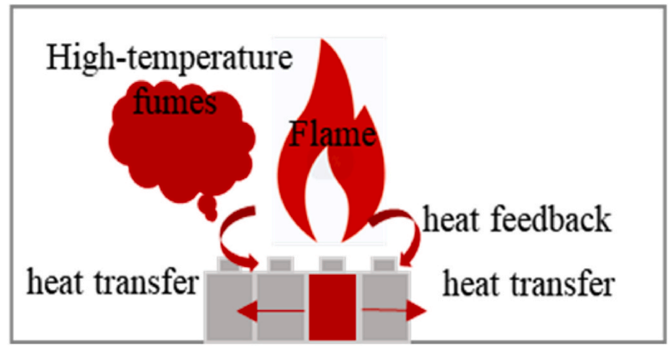
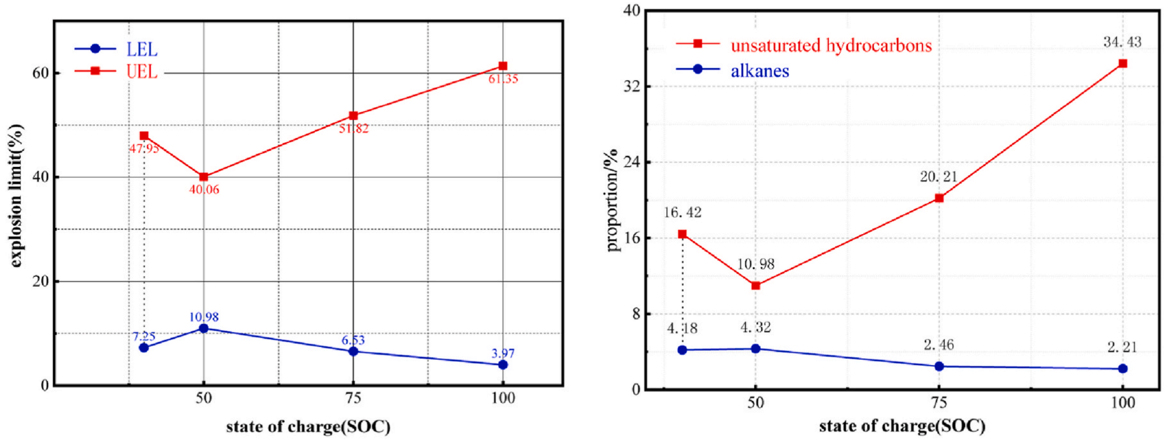


Fig. 10. Schematic diagram illustrating the potential hazards associated with TR in LIBs.

The aforementioned studies have primarily focused on individual batteries. However, single-cell TR initiates domino-effect thermal propagation in battery modules, which will result in more severe consequences. As a result, researchers have shifted their focus to examine the TR propagation characteristics of LIBs in these configurations. Zhu et al. (2023) conducted an experimental and analytical investigation into the TR propagation characteristics of ternary pouch cells under various states of charge and discharge and different spacing configurations. They found that the state of charge and discharge significantly influence the maximum temperature, mass loss, and flame jet behavior, yet the spacing between cells has a greater effect on the time and duration of TR propagation. Chen et al. (2020a) examined the thermal failure propagation behavior of Li-ion batteries through full-scale combustion experiments and revealed that simultaneous combustion of multiple cells will exacerbate the combustion rate, leading to higher mass loss rates and heat release rates within a battery pack. Similarly, Liu et al. (2020b) experimentally studied the self-heating fire of open-circuit battery stacks and found that the critical ambient temperature for self-heating fire decreases with the increase in the cell state of charge, the number of cells and the size of the stacks.

Furthermore, for multilayer tightly stacked large-scale stacks, such as those in containers and warehouses, Liu et al. (2020b) predicted that the critical ambient temperature for self-ignition may decrease to 30 °C based on Frank-Kamenetskii analysis (Sun and Ding, 2005), as shown in Fig. 13. However, given the cost and safety concerns associated with full-scale experiments, researchers gradually turned to simulations to explore the self-heating laws of LIBs. He et al. (2021) established a self-heating model to determine the critical ambient temperature and demonstrated that the use of this critical ambient temperature is more appropriate for evaluating safe storage conditions than adopting a critical temperature rise rate. Furthermore, their model results indicate that the critical ambient temperature decreases as the size of the battery stack increases due to scale effects, which in turn elevates the likelihood of TR during storage and transportation. In addition, Li et al. (2023b) assessed the transportation risks of LIBs, incorporating self-heating



(a) Variation curve of exhausted gas explosion limit of different SOC batteries

(b) The proportion of the total content of unsaturated hydrocarbons and alkanes varies with SOC

Fig. 11. (a) Variation curve of exhausted gas explosion limit of different SOC batteries; (b) The proportion of the total content of unsaturated hydrocarbons and alkanes varies with SOC (Zhang et al., 2022c).

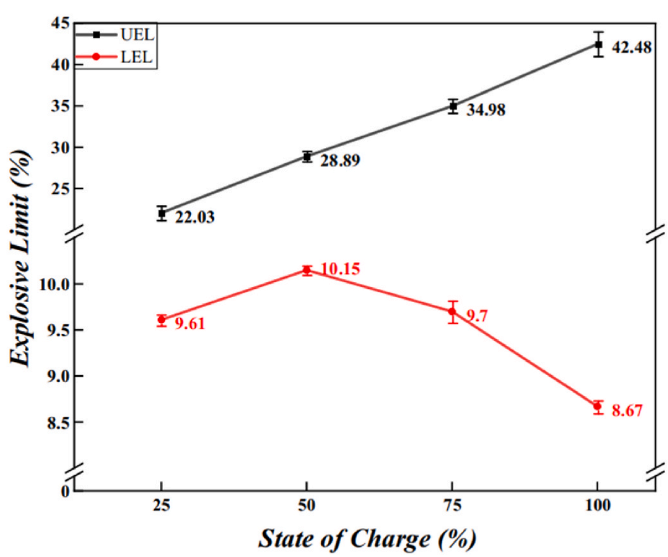


Fig. 12. Variation of battery vent gas explosion limits for different SOC batteries (Zhang et al., 2022b).

considerations into a dynamic Bayesian assessment model. Their predictions showed that the value of transportation risk and the severity of transportation accidents increase with the extension of the transportation time of LIBs.

Confined spaces (e.g., shipping containers) exacerbate thermal abuse hazards. Liu et al. (2022b) found that the total amount of combustible gases accumulated in confined spaces is higher than that in open environments, thereby increasing the potential risk of deflagration. In addition, experimental results indicated that the toxicity hazards of fire effluents are more severe in confined spaces (Liu et al., 2023). The confined space inside such shipping containers has a more pronounced impact on the TR propagation characteristics of battery modules. This effect arises mainly from the accumulation of high-temperature gases and smoke released during TR within the enclosed environment. Specifically, these hot vented substances can heat the batteries that have not yet experienced TR and contribute 27.3 % of the total heat during heat transfer (Peng et al., 2025). Simultaneously, the flames produced by TR impact the top of the packaging, forming a ceiling jet fire. The thermal radiation from these flames further heats the surrounding batteries (Zhang et al., 2022d, 2024; Zhao et al., 2024; Song et al., 2025) (see Fig. 14).

In summary, extensive studies have investigated the TR hazards associated with LIBs under thermal abuse scenarios. However, most research has focused on battery safety in open or well-ventilated environments, which differs from transportation scenarios, where batteries are typically stored in confined containers. Future work should therefore focus on quantifying the coupled effects of thermal abuse and confinement on TR behavior and establishing a standardized database of transportation-scenario TR risks to improve battery transportation safety.

3.3. Other factors

In addition to mechanical and thermal abuse, two scenario-specific environmental factors that are closely associated with major LIB transport modes can significantly influence battery TR behavior, namely low-pressure environments and high-salinity environments.

With the vigorous promotion of energy transformation in high-altitude areas, the application of LIBs in fields such as new energy vehicles and energy storage power stations is also increasing. In air transportation scenarios, where many cargo aircraft are unpressurized, LIBs are typically exposed to low-pressure environments. This has motivated studies examining the TR characteristics of LIBs under low-pressure conditions (Liu et al., 2021, 2022d; Sun et al., 2019, 2022b; Wang et al., 2020, 2025d). Chen et al. (2019b) conducted experimental studies on the TR of LFP and LCO batteries in Lhasa and Hefei, respectively. Their findings indicated that while ambient pressure has a minimal influence on the mass loss of both batteries during combustion, it has a more substantial impact on the heat of combustion. Specifically, the total heat release under high pressure is relatively larger than that under low pressure. Xie et al. (2020) observed that as the external pressure decreases, the TR initiation time and temperature of $LiFePO_4$ batteries also decrease, whereas the combustion time increases. They attributed the increased likelihood of TR under low-pressure conditions to the larger pressure differential, which facilitates the opening of the rupture disc and the entry of air. Conversely, Liu et al. (2022c) reported that low pressure can weaken both external flaming combustion and the internal TR reaction during the venting stage. This dual effect ultimately

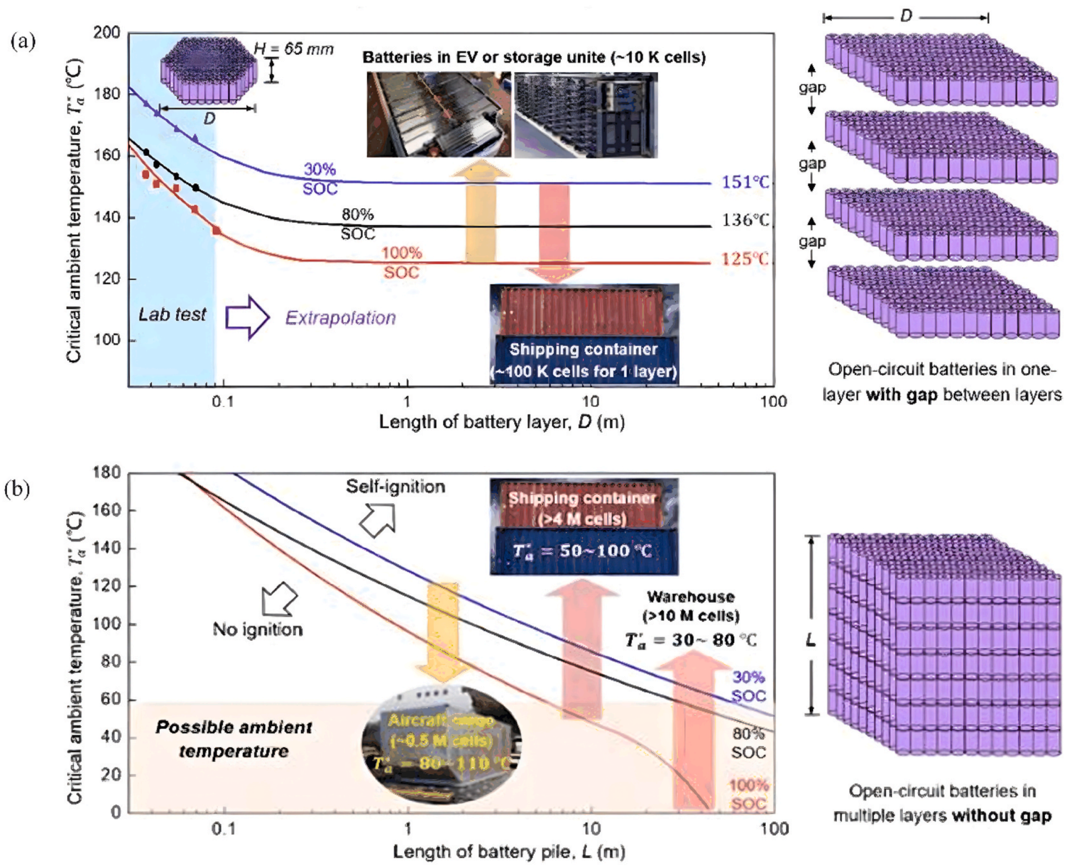


Fig. 13. Extrapolation of the critical ambient temperatures of self-ignition for battery stacks during storage and transportation (Liu et al., 2020b): (a) single layer or multilayer with gaps; (b) multi-layer dense packaging.

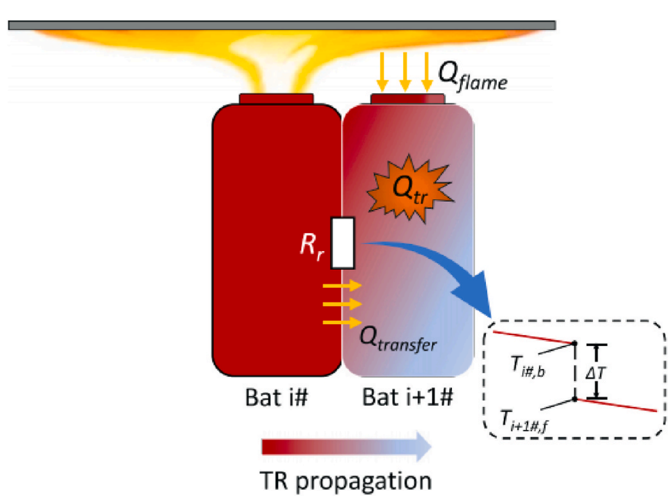


Fig. 14. The schematic of heat transfer between adjacent batteries under ceiling flame (Zhang et al., 2024).

increases the thermal runaway temperature of ternary batteries. In addition, the external ambient pressure also affects the TR propagation characteristics of a battery module. As the ambient pressure decreases, the TR propagation rate in ternary LIB modules tends to decrease (Liu et al., 2022c), whereas it tends to increase in LFP modules (Jia et al., 2022). The type of electrical connection between batteries also impacts the TR propagation characteristics under low-pressure conditions (Liu et al., 2022d). For parallel-connected ternary battery modules, a decrease in ambient pressure initially leads to an increase in the propagation rate due to reduced cooling efficiency, followed by a decrease as a result of diminished electrolyte levels after venting. Cook et al. (2020) investigated the impact of an ultra-low pressure environment (0.2 kPa) on the cycling performance of NCM523 battery cells. Their findings indicated that the failure of batteries under ultra-low pressure conditions is primarily associated with a rapid increase in internal resistance.

In contrast, high-salt-concentration environments are a key risk in maritime transport, where LIBs are exposed to humid, high-salt conditions (e.g., seawater mist) that can corrode battery casings and internal components, compromising transportation safety. To investigate this, Tao et al. (2020) conducted immersion tests on LCO batteries using a 3.5 % NaCl solution, assessing the fire risk of a battery under varying immersion durations through cone calorimeter tests. The experimental results indicated that with increased immersion time, the ignition time (time of flame appearance) first decreased and then increased, while the combustion duration increased initially and then plateaued, accompanied by a decrease in mass loss. Similarly, Wang et al. (2023c) studied the risks of TR in NCM622 batteries by immersing them in 2.5 % and 5 % NaCl solutions for 2 h at different states of charge. The results revealed that higher salt concentrations correlate with a higher TR trigger temperature and a shorter time required to initiate TR.

This section summarizes and analyzes the key influencing factors and underlying mechanisms during LIB transportation (as shown in Fig. 15), and systematically identifies the limitations of existing research as well as priorities for future research. However, in actual transportation scenarios, batteries frequently experience coupled multi-factor conditions. Such coupling not only amplifies the hazards of individual factors s but also can introduce additional failure pathways, leading to a reduced TR trigger threshold and accelerated evolution. Therefore, based on single-factor studies, it is imperative to strengthen research on multi-factor

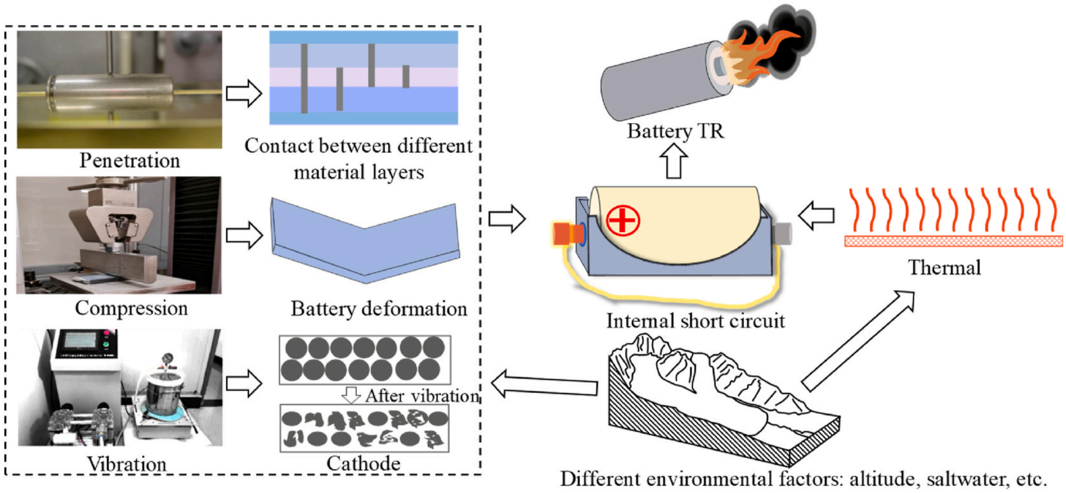


Fig. 15. Factors of TR during battery transportation and underlying mechanisms.

coupling mechanisms and quantify their synergistic effects. This will more accurately characterize safety behavior under realistic transportation conditions and provide a more robust basis for developing risk prevention and mitigation technologies. Additionally, considering the formidable challenges associated with conducting comprehensive experimental research due to the high concentration of LIBs in transportation scenarios, numerical simulation presents a promising approach for investigating the hazards of TR in large quantities of densely packed batteries within confined spaces.

4. Technical solutions for the safe transportation of lithium-ion batteries

4.1. Ventilation and heat dissipation strategies

The LIBs are typically densely arranged during transportation, so foam cotton is used for buffer protection. Multi-layer batteries are vertically stacked and supported by bottom trays to ensure secure bundling, but this packaging places the battery stack in a confined transportation space—where heat dissipation is particularly challenging in hot summer months (Mao et al., 2023). In practical transportation scenarios, dedicated thermal management systems are rarely implemented, and temperature regulation relies primarily on ventilation and passive heat dissipation rather than active cooling. What is more, existing research predominantly addresses thermal management strategies for batteries in electric vehicles and energy storage systems, where batteries are in use. These mature strategies include air cooling (natural/forced) (Dubey et al., 2023; Drame et al., 2024; E et al. (2020); Yang et al., 2020; Wang et al., 2023a; Wang et al., 2014; Zhang et al., 2022a; Luo et al., 2023), liquid cooling (Liu et al., 2022a; Zhao et al., 2015), phase change material cooling (Guo et al., 2022; Yan et al., 2016; Mohammadi and Taghilou, 2024) and heat pipe cooling (Chen and Li, 2020; Alihosseini and Shafaee, 2021; He et al., 2024; Zhang et al., 2025).

Table 4
Comparison of different cooling systems.

Cooling methods	Advantages	Disadvantages
Air cooling	Simple structure, low cost, easy maintenance	Low thermal conductivity, limited heat dissipation
Liquid cooling	High thermal conductivity, effective cooling	Complex structure, large weight, leakage problems
Phase change material cooling	Simple structure, low energy consumption	Leakage problems, high cost
Heat pipe cooling	High thermal conductivity, low weight	High cost, complex structure

Table 4 elaborates the advantages and disadvantages of each cooling technique. Among them, air cooling has advantages of simple structure, low cost, and easy maintenance—key merits that align well with the practical demands of LIB transportation scenarios (e.g., limited space, need for long-term reliability, and cost-effectiveness). Moreover, relevant studies have confirmed that increasing ventilation rate can reduce gas concentrations and shorten explosion duration in battery packs (Wang et al., 2023a). Therefore, ventilation-based air cooling is regarded as the most feasible heat dissipation approach for transported LIBs.

Scholars have further optimized air-cooling efficiency through battery arrangement design. Wang et al. (2014) explored the thermal performance of battery modules with different arrangements based on CFD and a single-cell aggregate model. They found that forced air cooling performed optimally with a top-mounted fan and a cubic arrangement, whereas a hexagonal arrangement offered the best space utilization. Dubey et al. (2023) investigated the temperature distribution of LIBs with different aspect ratios under different ventilation methods, as shown in Fig. 16. They found that cells with a medium length-to-diameter ratio (3.61) exhibited the lowest average temperature. Cells with larger aspect ratios showed the lowest radial temperature heterogeneity. Moreover, cells with a smaller aspect ratio achieved faster cooling rates regardless of the ventilation method. E et al., 2020 compared 16 LIBs in different arrangements and found that 4×4 outperforms 2×8, straight arrangements outperform staggered ones, and upper inlet-lower outlet ventilation is most effective. Their earlier study (E et al., 2018) also noted that the cooling performance of air inlets and outlets located on different sides is better than that of those located on the same side. Furthermore, the use of baffles can greatly improve the thermal performance of the transverse inlet and outlet air cooling strategy. The optimal cooling performance can be obtained when the airflow inlets and outlets are located on different sides of the chassis, and baffles are used.

However, these air-cooling studies primarily target batteries in use, whereas transportation scenarios differ in three key respects: transported LIBs are typically shipped in much larger quantities, remain in an open-circuit state (unlike the energized state of in-use batteries), and are enclosed in protective liners and stacked on trays (rather than housed within a vehicle chassis). Therefore, the applicability and achievable effectiveness of air-cooling strategies developed for in-use batteries under transportation conditions require further investigation.

4.2. Thermal monitoring

With the advancement of intelligent transportation systems, effective track monitoring, smoke detection, and temperature warning systems

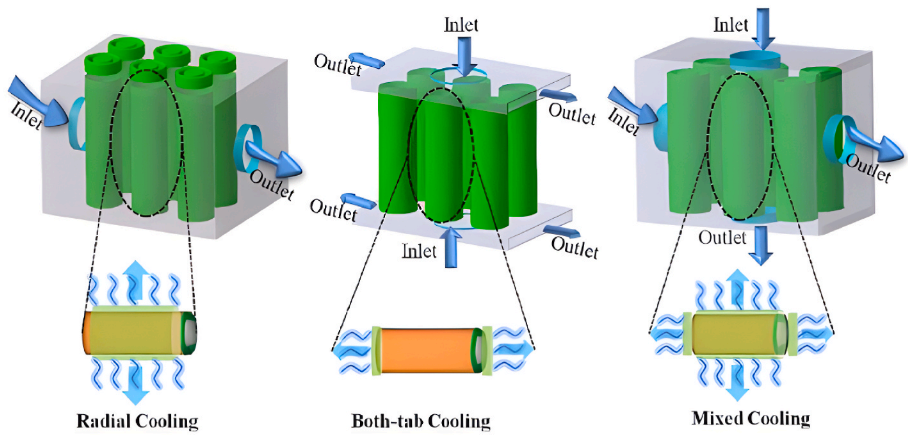


Fig. 16. Schematic diagram of different ventilation and cooling methods (Dubey et al., 2023).

can substantially enhance risk prediction during the transportation of LIB. Even in the event of a fire incident, these measures can help minimize losses. However, several technical challenges remain for the transportation of large quantities of LIBs, including how to effectively monitor battery safety status, which parameters to use for reliable early warning of TR, and how to optimize alarm placement.

Current battery TR early warning research is in a critical stage, but traditional methods (relying on voltage, current, impedance) are unsuitable for open-circuit transported batteries. Temperature-based early warning faces limitations: surface-internal temperature differences (due to heat conduction) cause delayed surface temperature warnings (Parhizi et al., 2017; Dong et al., 2025). To address this, Mei et al. (2023) developed a compact multi-functional fiber optic sensor (12 mm in length and 125 μm in diameter) designed to be embedded inside the battery to continuously monitor internal temperature during battery TR. However, measuring the internal temperature often requires specialized battery designs or destructive instrumentation. Additionally, the high cost of these sensors makes it difficult for widespread implementation.

Alternative early warning methods based on other parameters are also being explored. Chen et al. (2023) proposed expansion force as a reliable warning signal, which was experimentally demonstrated to provide a longer lead time for evacuation and rescue compared to voltage and temperature signals. Yang et al. (2023) found that the generation of gas-based signals precedes the TR of the battery by a few minutes, which provides new insights into the early safety warning of LIBs. Chen et al. (2020c) showed high-SOC batteries have violent oscillatory overpressure release, and pressure monitoring works for high external heat source scenarios.

A synthesis of the aforementioned studies indicates that single-parameter monitoring approaches (based on voltage, temperature, force, or gas) exhibit notable limitations in responsiveness and reliability when applied to complex environments. While gas and force signals may precede significant temperature rises, their reliability can be compromised by environmental disturbances in the absence of cross-validation with other indicators. To overcome these limitations and leverage the complementary strengths of different diagnostic signals, this study proposes integrating force–thermal–gas multi-dimensional signal detection into transport packaging to develop intelligent packaging, as shown in Fig. 17. Specifically, expansion force sensors can be installed on the sidewalls of the packaging to enable early warning of TR. This is attributed to the fact that during the incubation phase of TR, exothermic side reactions within the battery generate gases and electrolyte vapors (Li et al., 2024c), leading to surface expansion and abnormal inter-battery expansion forces. Additionally, temperature, pressure, and gas sensors can be positioned atop the packaging. When the internal gas pressure exceeds the safety valve's opening threshold, the instantaneous release of high-temperature gases impacts the top of the packaging, with gas temperatures surpassing 100 °C and pressures reaching up to 0.5 MPa (Mao et al., 2024). Concurrently, the gas concentration inside the packaging rapidly increases due to gas release and diffusion. By integrating multi-dimensional signal detection, the complementary strengths of different signals can be leveraged to promptly capture abnormal battery signals, identify the stage of thermal runaway development, and improve detection reliability.

Furthermore, the emerging neural network algorithm boasts robust capabilities in nonlinear modeling and complex data processing (Huang et al., 2025b; Chen et al., 2025). Therefore, the integration of multi-dimensional signal detection technologies with neural network

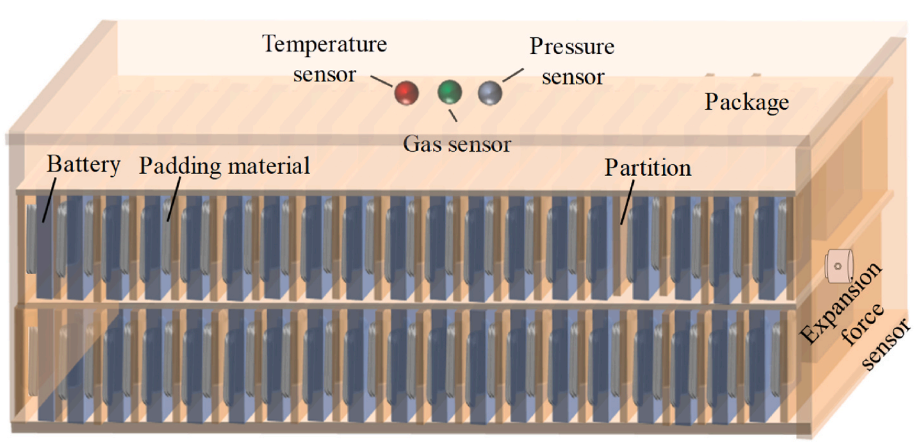


Fig. 17. Intelligent battery transport packaging.

algorithms during transportation can enhance the capability and accuracy of TR prediction.

4.3. Fire safety design

The simplified TR mechanism can be described using a LIB fire triangle (Mammacıoğlu and Coskun, 2025), as shown in Fig. 18. During TR of LIBs, the internal temperature increases continuously accompanied by gas evolution, which can culminate in fire and explosion (Jaguemont and Bardé, 2023; Peng et al., 2024; Wang et al., 2024a). Once exothermic reactions are triggered under extreme conditions, the battery can provide the key elements required for sustained combustion. This is because heat, various combustible substances, and oxygen are generated during the TR process. Therefore, it is necessary to adopt efficient suppression and extinguishing methods in a timely manner.

Fire extinguishing agents for LIBs act through four core mechanisms: physical isolation of the combustion interface, smothering (oxygen dilution), cooling (lowering temperatures below ignition thresholds), and chemical suppression (disrupting combustion reaction chains).

Solid extinguishing agents, dominated by dry powder formulations, consist of fire-retardant inorganic salts and additives processed into fine powders (Guo et al., 2023). Their primary action relies on oxygen isolation, cooling of the combustion zone, and interference with chemical reaction pathways. Meng et al. (2020) demonstrated that dry powder can extinguish visible LIB flames under proper application conditions, but a critical limitation remains: it does not effectively suppress ongoing internal exothermic reactions, leading to continued battery temperature rise after flame extinction. To address this gap, some scholars have optimized traditional dry powder extinguishing agents to more effectively suppress LIB fires (He et al., 2025; Li et al., 2024b). For example, Li et al. (2023c) studied a commercial dry powder fire extinguishing agent composed of inorganic phase change materials and applied it to fire-suppression experiments on LIB fires, as shown in Fig. 19. Their results showed that the composite dry powder agent can not only extinguish LIB fires but also suppress thermal runaway propagation.

The gaseous fire extinguishing agents exhibit excellent electrical insulation properties during fire suppression, along with being non-corrosive and leaving no residue, making them particularly suitable for extinguishing live electrical fires. Among them, CO_2 acts primarily by reducing or displacing ambient oxygen to achieve fire suppression (Ubaldi et al., 2024). However, LIBs generate oxygen during TR, weakening the smothering effect of CO_2, and re-ignition is common when using CO_2 to suppress LIB fires (Xu et al., 2020). Thus, CO_2 is ineffective for extinguishing LIB fires. Halon replacements like heptafluoropropane (C_3HF_7) exhibit strong electrical fire-extinguishing capacity but react with LIB combustion products to produce highly corrosive, toxic HF, requiring strict concentration control (Yu et al., 2025) that is difficult to maintain in dynamic transport environments. Another Halon alternative, perfluorohexanone ($C_6F_{12}O$), has gained attention for its excellent environmental protection characteristics (with

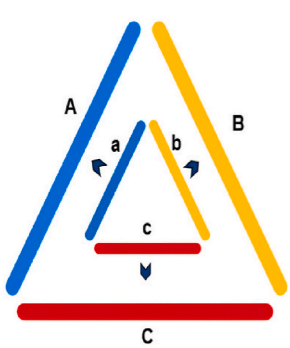


Fig. 18. LIB fire triangle (Mammacıoğlu and Coskun, 2025).

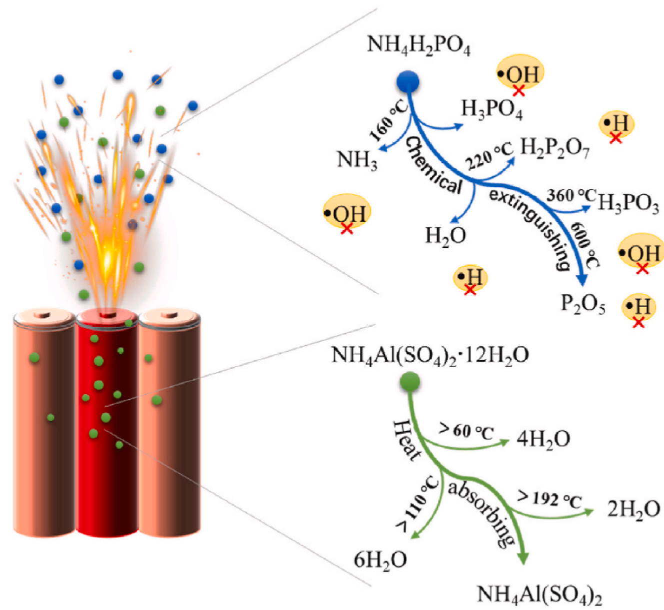


Fig. 19. Fire extinguish and cell cooling mechanism of composite dry powers fire extinguishing agent on battery module fires (Liu et al., 2023).

zero depletion potential (ODP)). Meng et al. (2023b) demonstrated that perfluorohexanone absorbs more heat via vaporization than heptafluoropropane, and Zhang et al. (2023) confirmed its ability to extinguish large-scale battery module fires and inhibit TR propagation in real-scale tests. However, Liu et al. (2022e) identified a critical drawback: increased perfluorohexanone dosage correlates with higher emissions of harmful gases, introducing secondary environmental and health risks in confined transport spaces. Liquid nitrogen, a cryogenically formed liquid state of nitrogen, exhibits a remarkable effect in preventing and controlling TR in batteries, thereby showing great application potential (Huang et al., 2021). Cao et al. (2023) studied the effectiveness of liquid nitrogen in restraining the TR of LIBs and reported that it exhibits significant efficacy in cooling the battery and inhibiting the TR as well as its propagation.

Liquid extinguishing agents, with water as the main component, can be formulated with additives or assisted by auxiliary methods to enhance fire suppression and cooling performance. Water mist, a common liquid agent, suppresses LIB fires by cooling and diluting combustible gases (Xu et al., 2022; Wang et al., 2025e). However, traditional water mist has been reported to have difficulty reaching the battery surface and may increase hydrogen fluoride production (Larsson et al., 2014). To address these limitations, Li et al. (2025) developed a composite additive-enhanced water mist using nonionic surfactants, which improves wetting and penetration capabilities while maintaining eco-friendliness—critical for dense battery stacks in transport. Foam extinguishing agents, another liquid category, offer higher viscosity and lower density than water, enabling better adhesion to battery surfaces. Xu et al. (2025) synthesized a new gel foam based on konjac gum (KGM) and sodium silicate (WG) for extinguishing LIB fires. Their experiments showed that the cooling rate of the battery surface temperature was 3.47 $°C·s^{-1}$, and that of the battery flame was 32.65 $°C·s^{-1}$, indicating that this gel foam can effectively suppress thermal runaway in LIBs. Table 5 shows the advantages and disadvantages of various fire suppression methods.

Notably, LIB transportation scenarios are dominated by confined spaces, where combustion dynamics differ significantly from open environments (Yan et al., 2021). Sun et al. (2022a) investigated the effects of different extinguishing agents on TR propagation in batteries. They found that heptafluoropropane has limited ability to suppress TR propagation. Although perfluorohexanone cannot completely prevent

Table 5
Comparison of advantages and disadvantages of various fire extinguishing agents.

Physical state classification	Typical fire extinguishing agents	Advantages	Disadvantages
Solid extinguishing agents	Dry powder extinguishing agents	Wide adaptability, Low cost, and good storage stability	LIB fires are prone to re-ignition, High residue content, Dry powders with high conductivity may cause secondary short circuits
Gaseous extinguishing agents	CO_2	No residue, Excellent electrical insulation	Poor cooling capacity, LIB fires are prone to re-ignition
	Heptafluoropropane	High fire extinguishing efficiency, No residue, Excellent electrical insulation	Decompose into toxic gases, complicated operation
	Perfluorohexanone	High fire extinguishing efficiency, No residue, Excellent electrical insulation	Decompose into toxic gases, complicated operation
	Liquid nitrogen	Efficient fire extinguishing effect and cooling ability, No residue, No pollution	Challenges in storage and transportation, Nozzle steam easily congeals to ice plugging pipelines
Liquid extinguishing agents	Water mist	Low cost, Significant cooling effect, Environmental protection	Aggravate short circuit or electrolyte leakage
	Foam extinguishing agents	Efficient fire extinguishing effect, Capable of covering combustible surfaces	Poor low-temperature stability, Complex preparation with strict ratio requirements

TR propagation, it can decrease battery temperature, slow the heat transfer rate, and prolong the propagation time. In contrast, water spray provides the most effective cooling and can prevent TR propagation. Subsequently, Huang et al. (2025a) examined the suppression effect of perfluorohexanone on the TR of NCM soft-pack LIB in a confined space. They observed that the perfluorohexanone demonstrates notable suppression of LIB fires, extinguishing visible flames within 3 s at a critical extinguishing dose of at least 2.62 kg/kWh.

Based on the above analysis, it can be concluded that dry powder agents and CO_2 exhibit poor cooling efficiency for TR batteries; even if open flames are extinguished, the batteries may re-ignite. Heptafluoropropane and perfluorohexanone demonstrate excellent chemical inhibition effects on fires, while liquid extinguishing agents such as water mist and liquid nitrogen exhibit strong cooling capabilities, making them suitable for suppressing LIB fires. In packaged shipments of LIBs, cells are enclosed in individual packages and consolidated into a larger transport unit. If TR initiates in a cell located within a centrally positioned package in the transport unit, the tight spacing can intensify heat transfer to adjacent cells, thereby triggering severe cascading TR propagation throughout the shipment. This poses a significant fire risk and underscores the importance of rapid-action liquid fire-extinguishing agents. Where conditions permit, perfluorohexanone can be used as an auxiliary disposal measure, as its efficient cooling performance can delay the TR the initial fires. Furthermore, it is imperative to optimize existing fire extinguishing agents and advance the development of novel fire extinguishing agents to enhance the fire suppression capabilities for LIB fires and improve the safety of LIB transportation.

5. Standards and test requirements

The "United Nations Recommendations on the Transport of Dangerous Goods" are designed to address all aspects of transportation to ensure international consistency, which is updated every two years. They incorporate a classification system using UN numbers to categorize substances that present significant hazards during transport. According to the UN model regulations, LIBs are classified as Class 9 Dangerous Goods (United Nations (UN), 2023a). To distinguish LIB transport scenarios, UN numbers are categorized into four types, as listed in Table 6. It should be noted that in previous versions, UN3171 was used to classify all battery-powered vehicles uniformly. However, in the latest regulations, a dedicated number UN3556 has been introduced specifically for vehicles powered by LIBs. Vehicles here refer to self-propelled apparatus designed to carry one or more persons or goods, including electric vehicles, motorcycles and bicycles, etc. Additionally, UN3536 refers to LIBs or lithium metal batteries installed in a cargo transport unit and designed solely to provide power external to that cargo transport unit, such as energy storage cabinets, which is not considered in this paper.

Table 6
UN numbers and detailed provisions of LIBs.

UN No.	Clarification	Special provisions	Packing instruction	Class
UN3480	LIBs (including lithium-ion polymer batteries)	188 230 310 348 376 377 384 387	P903 P908 P909 P910 P911 LP903 LP904 LP905 LP906	9
UN3481	LIBs contained in equipment or LIBspacked with equipment (including lithium-ion polymer batteries)	188 230 310 348 360 376 377 384 387 390	P903 P908 P909 P910 P911 LP903 LP904 LP905 LP906	
UN3556	Vehicle, LIBs powered	384 388 405	P912	
UN3536	Lithium batteries installed in cargo transport units (including LIBs or lithium metal batteries)	389	N/A	

Note: (1) The letters "P" means packagings other than intermediate bulk containers and large packagings; (2) the letters "LP" means large packagings.

5.1. Testing requirements

The UN Manual of Tests and Criteria is regarded as one of the key standards for transportation testing, outlining the testing methods and procedures for various transported substances. Part III, Section 38.3 of the manual stipulates a series of tests that must be conducted on lithium-ion cells and batteries prior to transport. To simulate the potential hazards that LIBs may encounter during transportation, this series of tests include a total of eight tests: 1) altitude simulation test, 2) thermal test, 3) vibration test, 4) shock test, 5) external short circuit test, 6) impact/crush test, 7) overcharge test, and 8) forced discharge test (United Nations (UN), 2023c), as shown in Table 7. The specific testing procedures and the number of tests vary depending on the battery specifications and types. As shown in Table 8, the manual provides classification standards based on battery specifications. Regardless of the mode of transportation, it is mandatory for LIBs to undergo UN 38.3 reliability tests and obtain a test report (Farrington, 2001). The testing of these batteries can be conducted by third-party organizations or manufacturers with relevant testing qualifications (Huo et al., 2017).

However, the current test standard has the following two main deficiencies: First, the criterion for determining whether the battery passes the external short-circuit test is that its temperature should not exceed 170 °C. However, with increasing LIB size and capacity, surface temperature fields become increasingly non-uniform, which can compromise temperature measurement accuracy and, in turn, undermine the

Table 7
The requirements for each test specified in UN 38.3

NO	Test name	Test purpose	Test procedure
T.1	Altitude simulation	This test simulates air transport under low-pressure conditions.	Test cells and batteries shall be stored at a pressure of 11.6 kPa or less for at least 6 h at ambient temperature (20 + 5 °C).
T.2	Thermal test	This test assesses cell and battery seal integrity and internal electrical connections. The test is conducted using rapid and extreme temperature changes.	Test cells and batteries are stored at 75 ± 2 °C for ≥6 h, then −40 ± 2 °C for ≥6 h (max 30min transition), with this cycle repeated 10 times, followed by 24 h storage at 20 ± 5 °C; large ones require ≥12 h at extreme temperatures.
T.3	Vibration	This test simulates vibration during transport.	A sinusoidal vibration test is adopted, with a frequency range of 7 (1 g_n peak acceleration) ~ 200 (8 g_n peak acceleration) ~ 7 Hz and a duration of 1 min per cycle. Both cells and batteries shall undergo repeated tests in three perpendicular directions, with 12 cycles repeated in each direction, totaling 3 h.
T.4	Shock	This test assesses the robustness of cells and batteries against cumulative shocks.	Subjected to half-sine shock impacts with a peak acceleration of 150 g_n and a pulse duration of 6 ms. For each of the three mutually perpendicular mounting positions, 3 shocks are applied in both positive and negative directions, resulting in a total of 18 shocks.
T.5	External short circuit	This test simulates an external short circuit.	An external short circuit is applied at 55 ± 2 °C with an external resistance of less than 0.1 Ω, and the test lasts for at least 1 h.
T.6	Impact	These tests simulate mechanical abuse from an impact or crush that may result in an internal short circuit.	The test sample cell or component cell is to be placed on a flat surface. A 15.8 mm diameter bar is to be placed across the centre of the sample. A 9.1 kg mass is to be dropped from a heightof61 + 2.5 cm onto the sample.
T.7	Overcharge	This test evaluates the ability of a rechargeable battery or a single cell rechargeable battery to withstand an overcharge condition.	The charge current shall be twice the manufacturer's recommended maximum continuous charge current. The minimum voltage of the test shall be as follows: (a) when the manufacturer's recommended charge voltage is not more than 18 V, the minimum voltage of the test shall be the lesser of two times the maximum charge voltage of the battery or 22 V. (b) when the manufacturer's recommended charge voltage is more than 18 V, the minimum voltage of the test shall be 1.2 times the maximum charge voltage. Tests are to be conducted at ambient temperature. The duration of the test shall be 24 h
T.8	Forced discharge	This test evaluates the ability of a primary or a rechargeable cell to withstand a forced discharge condition.	Each cell shall be forced discharged at ambient temperature by connecting it in series with a 12 V D.C. power supply at an initial current equal to the maximum discharge current specified by the manufacturer.

Table 8
Specification classification of LIBs.

Battery specifications	Clarification
Small cell	A cell with a gross mass of not more than 500 g
Large cell	A cell with a gross mass of more than 500 g
Small battery	A battery with a gross mass of not more than 12 kg
Large battery	A battery with a gross mass of more than 12 kg

Note: (1) Cell means a single encased electrochemical unit (one positive and one negative electrode) which exhibits a voltage differential across its two terminals, and may contain protective devices. (2) Battery means two or more cells or batteries which are electrically connected together and fitted with devices necessary for use, for example, a case, terminals, marking or protective devices.

validity of the test. Second, existing standards specify limited requirements for test apparatus and control performance. The temperature cycling rate of existing equipment fails to accurately simulate the internal thermal diffusion process, and the temperature control system is unable to track the temperature difference between the battery surface and its interior in real time, resulting in limited detection sensitivity. Therefore, strengthening pre-transport safety testing specifications is warranted to facilitate the development and deployment of more advanced and reliable test equipment.

5.2. *Packaging requirements*

Lithium-ion cells and batteries should be packed following with "Recommendations on the Transport of Dangerous Doods-Model Regulations-VolumeII, 23 ed" (United Nations (UN), 2023b), as is shown in Table 6. Requirements differ for LIBs and LIB-powered vehicles due to varying battery conditions and weights. Generally, packaging for LIBs can utilize drums, cans, or boxes made from materials such as steel, aluminum, natural wood, plywood, reconstructed wood, paperboard or fiberboard, plastics, and other metals. These packages can be centrally loaded into large transportation units, such as shipping containers, truck compartments, and aircraft cargo holds. However, given the inherent hazards of lithium batteries, cells or batteries in packaging require basic protection to prevent damage from movement or repositioning, which could otherwise lead to mechanically abusive lithium battery fire hazards. Damaged or defective units need additional non-combustible, non-conductive insulating materials and padding to mitigate hazards. What's more, ventilation features may be incorporated into sealed packaging to prevent the accumulation of flammable gases produced by LIB TR, which could otherwise lead to explosion hazards. Other specific packing requirements can be found in the "Recommendations on the Transport of Dangerous Doods-Model Regulations-VolumeII, 23 ed". As shown in Fig. 20, the labelling requirements for LIB packages under different transportation conditions are displayed. For LIBs that comply with special provision 188, the package labels are marked according to UN numbers, using the labels shown in Fig. 20(a) and (b). For LIB packages not covered by Special Provision 188, the label shown in Fig. 20 (c) is used. Furthermore, a safety data sheet and a test passing report to demonstrate that the batteries have passed the safety tests should be prepared.

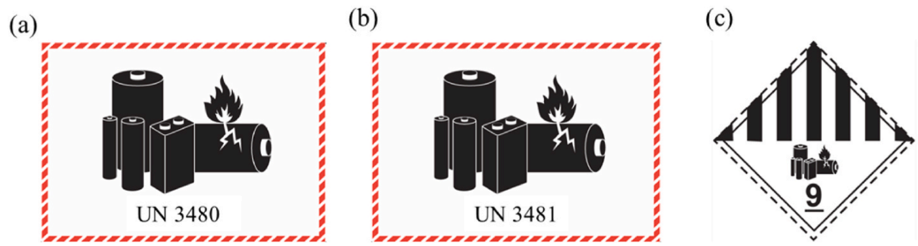


Fig. 20. Marks and labels for LIBs.

In practice, the selection of packaging materials and the methodology of packaging design play a critical role in ensuring the safe transportation of LIBs. Considering cost and weight factors, current packaging materials mainly consist of corrugated cardboard for fresh batteries, which unfortunately tend to ignite shortly after battery TR occurs, facilitating TR propagation. Thus, developing innovative packaging with early thermal anomaly detection and TR spread prevention—such as the intelligent design proposed in Section 4.3.2—would enhance incident control.

5.3. Other regulations

To ensure the safe transport of LIBs across different transportation modes, various international organizations have developed more detailed and stringent transportation regulations based on the framework of UN Model Regulations, as shown in Table 9. Each transportation mode has specific requirements tailored to the inherent risks and operational characteristics associated with that mode, leading to significant discrepancies in the regulations, particularly regarding the state of charge (SOC) of the batteries. For the air transport of LIBs, the regulations to be followed are established by two international organizations, namely ICAO and IATA. "Technical Instructions for the Safe Transport of Dangerous Goods by Air" developed by ICAO serves as the fundamental safety standard for air transportation, while IATA has developed more detailed operational guidelines "Dangerous Goods Regulations" based on these instructions. The regulations stipulate that the SOC of LIBs for air transport must not exceed 30 % as higher SOC levels significantly increase the risk of combustion. If not suppressed promptly, fires can lead to catastrophic accidents, including the potential destruction of the aircraft and loss of life (International Air Transport Association (IATA), 2025; International Civil Aviation Organization (ICAO), 2024). For the road transport of LIBs, they must comply with the "Agreement Concerning the International Carriage of Dangerous Goods by Road" (United Nations Economic Commission for Europe (UNECE), 2025). There are no restrictions on the state of charge of batteries in this regard. The transportation of goods by sea should comply with the "International Maritime Dangerous Goods Code" (International Maritime Organization (IMO), 2024). Additionally, there are specific requirements outlined in "Regulations concerning the International Carriage of Dangerous Goods by Rail" (Intergovernmental Organization for International Carriage by Rail (OTIF), 2025) for transporting LIBs by rail. Unlike air transport, these modes do not impose SOC restrictions on batteries which can be attributed to several factors. Firstly, longer transit times during which limiting SOC could cause excessive self-discharge and potential battery damage before reaching the destination. Secondly, in the event of a TR emergency response is more feasible due to the ability to stop and address the incident promptly.

In addition to these international regulations, different countries typically establish their own regulations for the transport of dangerous goods. For example, Title 49 of the Code of Federal Regulations governs the domestic transportation of LIBs in the United States across various modes (Pipeline and Hazardous Materials Safety Administration (PHMSA), 2025). However, there are notable differences between the U. S. regulations and the UN Model Regulations, particularly regarding

Table 9
Lithium-ion battery transportation specification standards.

Mode of transportation	Organization	Standard	Affiliation	Update cycle	Difference
Air	ICAO	Technical Instructions for the Safe Transport of Dangerous Goods by Air	International	Every 2 years	General regulatory principles
	IATA	Dangerous Goods Regulations	International	Every year	The provisions are more detailed and stringent
	CAAC	Specification for Transport of Lithium Batteries by Air Test for Lithium Batteries Transported by Air	Chinese	Dynamically revised (updated approximately every 3–5 years in recent years)	Certain clauses are refined, such as the content related to restrictions on spare lithium batteries
Road	UNECE	Agreement Concerning the International Carriage of Dangerous Goods by Road	International	Every 2 years in recent years	General regulatory principles
	MOT	Regulations Concerning Road Transportation of Dangerous Goods	Chinese	Every year in recent years	Separate the consignment list from the waybill accompanying the Goods
Rail	OTIF	The Regulation concerning the International Carriage of Dangerous Goods by Rail	International	Every 2 years	General regulatory principles
Sea	IMO	International Maritime Dangerous Goods Code	International	Every 2 years	General regulatory principles
	China MSA	Regulations on the Safety Management of Dangerous Goods Carried on Board Ships	Chinese	/	Some provisions have been refined in light of national conditions. For instance, ships are required to complete declaration procedures 24 h prior to entering or exiting ports; failure to do so within the specified timeframe will result in administrative penalties
All modes	PHMSA	Title 49 of the Code of Federal Regulations	American	Dynamically revised	The number of cells or batteries per package is unlimited

packaging requirements for damaged or defective cells and batteries. The UN Model Regulations stipulate that for a cell or battery with a ner mass more than 30 kg shall be limited to only one cell or battery per outer packaging. This restriction minimizes the risks associated with large, damaged batteries, as they present greater hazards in cases of TR. In contrast, U.S. regulations (49 CFR) do not impose such a restriction on the number of cells or batteries per outer package, offering more flexibility in packaging configurations. Additionally, the UN Model Regulations require that the inner packaging of damaged or defective cells must be surrounded by insulating and cushioning materials, and it must use Packing Group II packaging. These provisions aim to reduce the risk of accidental mechanical damage during transport. On the other hand, the U.S. regulations (49 CFR) emphasize similar requirements but additionally specify the use of non-metallic inner packaging and mandate the use of Packing Group I packaging, reflecting a more cautious approach to handling potentially dangerous goods. These enhanced packaging standards ensure that even in the event of a malfunction, the packaging can withstand more severe conditions. In China, "Specification for Transport of Lithium Batteries by Air" (Civil Aviation Administration of China (CAAC), 2018) issued by the Civil Aviation Administration of China (CAAC) is mandatory for air transportation of LIBs. For road transport, LIBs must meet JT/T 617-2018 "Regulations Concerning Road Transportation of Dangerous Goods" (National Technical Committee on Road Transport of Standardization Administration of China (SAC/TC 521), 2018).

Despite the broad alignment of most countries' transportation regulations with UN standards, discrepancies still exist, particularly in packaging requirements and other areas. Therefore, when transporting LIBs across borders, it is essential to carefully consider the differences between national standards to ensure compliance with all relevant regulations.

6. Conclusions and outlook

The rapid advancement of LIBs has driven a substantial rise in their global transportation. However, the complex and variable conditions encountered during transit have led to periodic safety incidents. Ensuring the safe transportation of these batteries has therefore become an urgent priority.

Currently, LIBs are transported via air, road, sea, and rail. Throughout these processes, batteries may be subjected to mechanical and thermal stresses that compromise their integrity. The use of buffer materials in packaging can effectively alleviate mechanical abuse, while appropriate heat dissipation measures are essential to minimize the risk of TR caused by insufficient heat dissipation. Among available options, air cooling stands out for its simplicity, cost-effectiveness, and ease of maintenance, making it a promising solution for enhancing the overall safety of LIB transportation.

TR is characterized by its sudden onset, severe consequences, and the difficulty of implementing timely rescue measures during transit. During transportation, integrating multi-dimensional signal detection with neural network algorithms can significantly enhance the timeliness and accuracy of TR prediction. In terms of fire suppression, liquid extinguishing agents are preferred. Where feasible, perfluorohexanone may be employed as an auxiliary measure—its efficient cooling capability can effectively delay the initial stages of combustion during TR.

International safety standards for battery transportation exist across modes, yet most remain generalized. Moreover, full alignment between national regulations and international frameworks has not been achieved, and discrepancies persist among different legal systems. Therefore, promoting mutual recognition of test results and simplifying cross-border transport procedures are critical issues requiring urgent attention. Continuous improvement of safety standards is also essential, especially as LIB energy density and size specifications increase. Test requirements and pass criteria must be rigorously evaluated for applicability and effectiveness. It is anticipated that more refined and intelligent testing equipment will serve as the primary defense in ensuring transportation safety.

In summary, ensuring the safety of LIB transportation requires multi-layered protective measures throughout the entire logistics chain. Future research should focus on developing integrated monitoring strategies, intelligent early-warning systems, multiphysics simulation validation, and novel fire-extinguishing agents to further enhance the safety and reliability of LIB transport.

CRediT authorship contribution statement

Lulu Song: Writing – original draft, Methodology, Investigation, Conceptualization. **Zhenhua Wang:** Writing – original draft, Methodology, Investigation, Conceptualization. **Yongchun Zhu:** Methodology. **Zhizuan Zhou:** Visualization, Conceptualization. **Boxuan Wang:** Methodology, Conceptualization. **Dong Wang:** Methodology. **Ulises Rojas Alva:** Writing – review & editing, Funding acquisition. **Lizhong Yang:** Methodology, Conceptualization. **Xiaoyu Ju:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing 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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Data availability

The authors are unable or have chosen not to specify which data has been used.

References

Air Cargo World, 2019. Cargo pallet catches fire at HKG, cause uncertain. https://aircargoworld.com/news/stakeholders/airports/cargo-pallet-catches-fire-at-hkg-cause-uncertain/.

Alihosseini, A., Shafaee, M., 2021. Experimental study and numerical simulation of a lithium-ion battery thermal management system using a heat pipe. J. Energy Storage 39, 102616. https://doi.org/10.1016/j.est.2021.102616.

Amiri, S., Chen, X., Manes, A., Giglio, M., 2016. Investigation of the mechanical behaviour of lithium-ion batteries by an indentation technique. Int. J. Mech. Sci. 105, 1–10. https://doi.org/10.1016/j.ijmecsci.2015.10.019.

Arief Budiman, B., Rahardian, S., Saputro, A., Hidayat, A., Pulung Nurprasetio, I., Sambegoro, P., 2022. Structural integrity of lithium-ion pouch battery subjected to three-point bending. Eng. Fail. Anal. 138, 106307. https://doi.org/10.1016/j.engfailanal.2022.106307.

Awan, U.S., Ghabraie, K., Zolfagharian, A., Eftekharnia, M., Rolfe, B., 2025. Cell geometry influences on the vibration performance of lithium-ion batteries. J. Energy Storage 109, 115227. https://doi.org/10.1016/j.est.2024.115227.

Bhoir, S., Michelini, E., Moser, J., Brivio, C., Paolone, M., 2025. A systematic review of thermal runaway in Li-ion batteries: pathways, detection techniques, and early warning models. Fut. Batter. 8, 100110. https://doi.org/10.1016/j.fub.2025.100110.

Brand, M.J., Schuster, S.F., Bach, T., Fleder, E., Stelz, M., Gläser, S., Müller, J., Sextl, G., Jossen, A., 2015. Effects of vibrations and shocks on lithium-ion cells. J. Power Sources 288, 62–69. https://doi.org/10.1016/j.jpowsour.2015.04.107.

Cao, Y., Wang, K., Wang, Z., Wang, J., Yang, Y., Xu, X., 2023. Utilization of liquid nitrogen as efficient inhibitor upon thermal runaway of 18650 lithium ion battery in open space. Renew. Energy 206, 1097–1105. https://doi.org/10.1016/j.renene.2023.02.117.

CBS News, 2024. Vincent Thomas Bridge remains closed as crews remove wrecked big rig from port of LA road. https://www.cbsnews.com/amp/losangeles/news/hazmat-in

vestigators-respond-47-freeway-closed-after-big-rig-with-lithium-batteries-flips-over-in-san-pedro/.
Chen, M., Li, J., 2020. Nanofluid-based pulsating heat pipe for thermal management of lithium-ion batteries for electric vehicles. J. Energy Storage 32, 101715. https://doi.org/10.1016/j.est.2020.101715.
Chen, M., Ouyang, D., Liu, J., Wang, J., 2019a. Investigation on thermal and fire propagation behaviors of multiple lithium-ion batteries within the package. Appl. Therm. Eng. 157, 113750. https://doi.org/10.1016/j.applthermaleng.2019.113750.
Chen, M., Ouyang, D., Weng, J., Liu, J., Wang, J., 2019b. Environmental pressure effects on thermal runaway and fire behaviors of lithium-ion battery with different cathodes and state of charge. Process Saf. Environ. Prot. 130, 250–256. https://doi.org/10.1016/j.psep.2019.08.023.
Chen, M., Ye, Q., Shi, C., Cheng, Q., Qie, B., Liao, X., Zhai, H., He, Y., Yang, Y., 2019c. New insights into nail penetration of Li-Ion batteries: effects of heterogeneous contact resistance. Batter. Supercap. 2, 874–881. https://doi.org/10.1002/batt.201900081.
Chen, M., Liu, J., Ouyang, D., Weng, J., Wu, X., Cao, S., Wang, J., 2020a. A large-scale experimental study on the thermal failure propagation behaviors of primary lithium batteries. J. Energy Storage 31. https://doi.org/10.1016/j.est.2020.101657.
Chen, S., Wang, Z., Yan, W., Liu, J., 2020c. Investigation of impact pressure during thermal runaway of lithium ion battery in a semi-closed space. Appl. Therm. Eng. 175, 115429. https://doi.org/10.1016/j.applthermaleng.2020.115429.
Chen, Y., Kang, Y., Zhao, Y., Wang, L., Liu, J., Li, Y., Liang, Z., He, X., Li, X., Tavajohi, N., Li, B., 2021. A review of lithium-ion battery safety concerns: the issues, strategies, and testing standards. J. Energy Chem. 59, 83–99. https://doi.org/10.1016/j.jechem.2020.10.017.
Chen, S., Wei, X., Zhang, G., Rui, X., Xu, C., Feng, X., Dai, H., Ouyang, M., 2023. Active and passive safety enhancement for batteries from force perspective. Renew. Sustain. Energy Rev. 187, 113740. https://doi.org/10.1016/j.rser.2023.113740.
Chen, J., Wang, Y., Guo, D., Liu, Z., Wang, Y., Li, S., Xu, W., Qian, L., Shen, Y., Sun, T., Han, X., Ouyang, M., Zheng, Y., 2025. Advancing battery research through large language models: a review. Innovation, 101091. https://doi.org/10.1016/j.xinn.2025.101091.
Cheng, D., Liu, Z., Xun, L., 2020. Discuss on safety of power Li-ion battery transport. Batt. Bimonth. 50, 172–176. https://doi.org/10.19535/j.1001-1579.2020.02.017.
Civil Aviation Administration of China (CAAC), 2018. Specification for Transport of Lithium Batteries by Air. China Civil Aviation Publishing House, China.
Cook, R.W., Swan, L.G., Plucknett, K.P., 2020. Failure mode analysis of lithium ion batteries operated for low Earth orbit CubeSat applications. J. Energy Storage 31, 101561. https://doi.org/10.1016/j.est.2020.101561.
Cover News, 2024. 2023 industry development report on power battery transportation released: road transport remains the primary mode for power battery logistics in China. https://www.thecover.cn/news/glN%2Bg9GcqaKH90qSdq8Jkw.
Dong, T., Huang, L., Liu, J., Kuang, Z., Sun, W., Wu, H., Cao, W., 2025. Advances and challenges in obtaining internal temperature for lithium-ion batteries. J. Power Sources 651, 237571. https://doi.org/10.1016/j.jpowsour.2025.237571.
Drame, O., Yahya, Z., Sarr, A., Mbow, C., 2024. Soumbedjioune tunnel in dakar: a case study for CFD modeling of fire-smoke extraction in a sinusoidal floor tunnel. Emerg. Manag. Sci. Technol. 4, 1. https://doi.org/10.48130/emst-0024-0011.
Dubey, D., Mishra, A., Ghosh, S., Reddy, M.V., Pandey, R., 2023. Geometry-influenced cooling performance of lithium-ion battery. Appl. Therm. Eng. 230, 120723. https://doi.org/10.1016/j.applthermaleng.2023.120723.
E, J., Yue, M., Chen, J., Zhu, H., Deng, Y., Zhu, Y., Zhang, F., Wen, M., Zhang, B., Kang, S., 2018. Effects of the different air cooling strategies on cooling performance of a lithium-ion battery module with baffle. Appl. Therm. Eng. 144, 231–241. https://doi.org/10.1016/j.applthermaleng.2018.08.064.
E, J., Zeng, Y., Jin, Y., Zhang, B., Huang, Z., Wei, K., Chen, J., Zhu, H., Deng, Y., 2020. Heat dissipation investigation of the power lithium-ion battery module based on orthogonal experiment design and fuzzy grey relation analysis. Energy 211, 118596. https://doi.org/10.1016/j.energy.2020.118596.
Farrington, M.D., 2001. Safety of lithium batteries in transportation. J. Power Sources 96, 260–265. https://doi.org/10.1016/s0378-7753(01)00565-1.
Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., He, X., 2018. Thermal runaway mechanism of lithium ion battery for electric vehicles: a review. Energy Storage Mater. 10, 246–267. https://doi.org/10.1016/j.ensm.2017.05.013.
Global News, 2024. Firefighters battle major blaze involving lithium batteries at Port of Montreal. https://globalnews.ca/news/10771623/port-of-montreal-fire-lithium-batteries-lockdown-notice/.
Guo, C., He, L., Yao, Y., Lin, W., Zhang, Y., Zhang, Q., et al., 2022. Bifunctional liquid metals allow electrical insulating phase change materials to dual-mode thermal manage the Li-ion batteries. Nano-Micro Lett. 14, 202. https://doi.org/10.1007/s40820-022-00947-w.
Guo, Y., Chang, Z., Tan, Z., 2023. Study on fire extinguishing mechanism of allophanate based on Monnex dry powder. Comput. Theor. Chem. 1230, 114361. https://doi.org/10.1016/j.comptc.2023.114361.
Hahn, A., Ruf, M., Doose, S., Kwade, A., 2025. Enhancing lithium-ion battery safety: a comparative study of separator performance under mechanical abuse. Fut. Batter. 6, 100064. https://doi.org/10.1016/j.fub.2025.100064.
He, X., Hu, Z., Restuccia, F., Yuan, H., Rein, G., 2021. Self-heating ignition of large ensembles of Lithium-ion batteries during storage with different states of charge and cathodes. Appl. Therm. Eng. 197, 117349. https://doi.org/10.1016/j.applthermaleng.2021.117349.
He, Z., Li, R., Yang, L., Mikulčić, H., Wang, J., Čuček, L., 2024. Performance analysis of a battery thermal management system based on phase change materials with micro heat pipe arrays. Energy Convers. Manag. 311, 118506. https://doi.org/10.1016/j.enconman.2024.118506.
He, Z., Guo, Y., Zhou, X., Zhang, H., 2025. Ammonium phosphate-based dry powder and $Na_2HPO_4 \cdot 12H_2O$ composite powder for suppressing the thermal runaway of lithium-ion batteries. J. Power Sources 654, 237819. https://doi.org/10.1016/j.jpowsour.2025.237819.
Hou, C., Hu, P., Chai, X., Guan, C., 2025. Study on the effect of active heating duration on thermal runaway in aviation power lithium-ion batteries. Case Stud. Therm. Eng. 73, 106569. https://doi.org/10.1016/j.csite.2025.106569.
Hu, L., Zhang, Z., Zhou, M., Zhang, H., 2020. Crushing behaviors and failure of packed batteries. Int. J. Impact Eng. 143, 103618. https://doi.org/10.1016/j.ijimpeng.2020.103618.
Hu, J., Liu, T., Tang, Q., Wang, X., 2022. Experimental investigation on thermal runaway propagation in the lithium ion battery modules under charging condition. Appl. Therm. Eng. 211, 118522. https://doi.org/10.1016/j.applthermaleng.2022.118522.
Huang, Z., Liu, P., Duan, Q., Zhao, C., Wang, Q., 2021. Experimental investigation on the cooling and suppression effects of liquid nitrogen on the thermal runaway of lithium ion battery. J. Power Sources 495, 229795. https://doi.org/10.1016/j.jpowsour.2021.229795.
Huang, J., Jin, J., Liang, J., He, Y., Chen, Y., 2025a. Experimental study on fire suppression of NCM lithium-ion battery by $C_6F_{12}O$ in a confined space. Appl. Therm. Eng. 259, 124932. https://doi.org/10.1016/j.applthermaleng.2024.124932.
Huang, Y., Wang, T., Xu, W., Zhao, Y., Liao, Y., Wang, J., Fan, Y., Wang, Z., 2025b. Study on thermal runaway characteristics of lithium batteries under high-rate charge/discharge and development of a deep learning-based early warning model. Energy 334, 137676. https://doi.org/10.1016/j.energy.2025.137676.
Huo, H., Xing, Y., Pecht, M., Zuger, B.J., Khare, N., Vezzini, A., 2017. Safety requirements for transportation of lithium batteries. Energies 10, 793. https://doi.org/10.3390/en10060793.
Intergovernmental Organization for International Carriage by Rail (OTIF), 2025. Convention concerning international carriage by rail (COTIF), appendix C-Regulations concerning the international carriage of dangerous goods by rail (RID). https://otif.org/fileadmin/docs/LegalTexts/COTIF/DangerousGoodsRID/RID/RID_2025_e_1_January_2025.pdf.
International Air Transport Association(IATA), 2025. Dangerous goods regulations. In: International Air Transport Association: Montreal, QC, Canada, 66 ed.
International Civil Aviation Organization (ICAO), 2024. Technical Instructions for the Safe Transport of Dangerous Goods by Air (Doc 9284), 2025-2026. International Civil Aviation Organization, Montreal, QC, Canada.
International Maritime Organization (IMO), 2024. International Maritime Dangerous Goods (IMDG) Code. IMO, Geneva, Switzerland.
Jaguemont, J., Bardé, F., 2023. A critical review of lithium-ion battery safety testing and standards. Appl. Therm. Eng. 231, 121014. https://doi.org/10.1016/j.applthermaleng.2023.121014.
Jia, Z., Huang, Z., Zhai, H., Qin, P., Zhang, Y., Li, Y., Wang, Q., 2022. Experimental investigation on thermal runaway propagation of 18,650 lithium-ion battery modules with two cathode materials at low pressure. Energy 251, 123925. https://doi.org/10.1016/j.energy.2022.123925.
Jia, Z., Wang, S., Qin, P., Li, C., Song, L., Cheng, Z., Jin, K., Sun, J., Wang, Q., 2023. Comparative investigation of the thermal runaway and gas venting behaviors of large-format $LiFePO_4$ batteries caused by overcharging and overheating. J. Energy Storage 61, 106791. https://doi.org/10.1016/j.est.2023.106791.
Keshavarzi, M.M., Gilaki, M., Sahraei, E., 2022. Characterization of in-situ material properties of pouch lithium-ion batteries in tension from three-point bending tests. Int. J. Mech. Sci. 219, 107090. https://doi.org/10.1016/j.ijmecsci.2022.107090.
Lai, W., Ali, M., Pan, J., 2014a. Mechanical behavior of representative volume elements of lithium-ion battery cells under compressive loading conditions. J. Power Sources 245, 609–623. https://doi.org/10.1016/j.jpowsour.2013.06.134.
Lai, W., Ali, M., Pan, J., 2014b. Mechanical behavior of representative volume elements of lithium-ion battery modules under various loading conditions. J. Power Sources 248, 789–808. https://doi.org/10.1016/j.jpowsour.2013.09.128.
Larsson, F., Andersson, P., Blomqvist, P., Lorén, A., Mellander, B.-E., 2014. Characteristics of lithium-ion batteries during fire tests. J. Power Sources 271, 414–420. https://doi.org/10.1016/j.jpowsour.2014.08.027.
Li, K., Li, J., Gao, X., Lu, Y., Wang, D., Zhang, W., Wu, W., Han, X., Cao, Y., Lu, L., Wen, J., Cheng, S., Ouyang, M., 2024c. Effect of preload forces on multidimensional signal dynamic behaviours for battery early safety warning. J. Energy Chem. 92, 484–498. https://doi.org/10.1016/j.jechem.2023.12.045.
Li, K., Li, D., Huang, X., Huang, G., Hu, J., Zhou, Q., Li, Y., 2022. Effect of mechanical vibration under low atmospheric pressure on thermo-runaway of lithium-ion battery. Chin. Batt. Industr. 26 (5), 228–233. https://doi.org/10.19996/j.cnki.ChinBatlnd.2022.05.003.
Li, H.G., Zhou, D., Zhang, M.H., Liu, B.H., Zhang, C., 2023a. Multi-field interpretation of internal short circuit and thermal runaway behavior for lithium-ion batteries under mechanical abuse. Energy 263, 126027. https://doi.org/10.1016/j.energy.2022.126027.
Li, J., Wang, J., Xie, J., Jiang, J., 2023b. Risk assessment of lithium-ion battery road transportation using the data-driven Bayesian network considering battery self-heating. Process Saf. Environ. Prot. 175, 715–731. https://doi.org/10.1016/j.psep.2023.05.088.
Li, X., Zhang, M., Zhou, Z., Zhu, Y., Du, K., Zhou, X., 2023c. A novel dry powder extinguishant with high cooling performance for suppressing lithium ion battery fires. Case Stud. Therm. Eng. 42, 102756. http://oi.org/10.1016/j.csite.2023.102756.
Li, H., Gu, J., Pan, Y., Liu, B., Zhang, C., 2024a. On the strain rate-dependent mechanical behavior of PE separator for lithium-ion batteries. Int. J. Impact Eng. 194, 105079. https://doi.org/10.1016/j.ijimpeng.2024.105079.

Li, X., Zhu, Y., Du, K., Zhou, X., 2024b. Experimental study on suppression of thermal runaway propagation of lithium-ion battery by salt hydrate based dry powder extinguishants. Case Stud. Therm. Eng. 60, 104629. https://doi.org/10.1016/j.csite.2024.104629.

Li, L., Zhang, Y., Li, Q., Zhan, W., Chen, Z., Chen, M., Cheng, Y., 2025. Efficient and environmentally friendly composite additive fine water mist for suppressing thermal runaway of lithium-ion batteries. J. Energy Storage 131, 115780. https://doi.org/10.1016/j.est.2025.115780.

Liu, B., Jia, Y., Yuan, C., Wang, L., Gao, X., Yin, S., Xu, J., 2020a. Safety issues and mechanisms of lithium-ion battery cell upon mechanical abusive loading: a review. Energy Storage Mater. 24, 85–112. https://doi.org/10.1016/j.ensm.2019.06.036.

Liu, Y., Sun, P., Lin, S., Niu, H., Huang, X., 2020b. Self-heating ignition of open-circuit cylindrical Li-ion battery pile: towards fire-safe storage and transport. J. Energy Storage 32, 101842. https://doi.org/10.1016/j.est.2020.101842.

Liu, Y., Niu, H., Li, Z., Liu, J., Xu, C., Huang, X., 2021. Thermal runaway characteristics and failure criticality of massive ternary Li-ion battery piles in low-pressure storage and transport. Process Saf. Environ. Prot. 155, 486–497. https://doi.org/10.1016/j.psep.2021.09.031.

Liu, J., Fan, Y., Xie, Q., 2022a. Feasibility study of a novel oil-immersed battery cooling system: experiments and theoretical analysis. Appl. Therm. Eng. 208, 118251. https://doi.org/10.1016/j.applthermaleng.2022.118251.

Liu, P., Sun, H., Qiao, Y., Sun, S., Wang, C., Jin, K., Mao, B., Wang, Q., 2022b. Experimental study on the thermal runaway and fire behavior of $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ battery in open and confined spaces. Process Saf. Environ. Prot. 158, 711–726. https://doi.org/10.1016/j.psep.2021.12.056.

Liu, Y., Niu, H., Liu, J., Huang, X., 2022c. Layer-to-layer thermal runaway propagation of open-circuit cylindrical li-ion batteries: effect of ambient pressure. J. Energy Storage 55, 105709. https://doi.org/10.1016/j.est.2022.105709.

Liu, Y., Niu, H., Xu, C., Huang, X., 2022d. Thermal runaway propagation in linear battery module under low atmospheric pressure. Appl. Therm. Eng. 216, 119086. https://doi.org/10.1016/j.applthermaleng.2022.119086.

Liu, Y., Yang, K., Zhang, M., Li, S., Gao, F., Duan, Q., Sun, J., Wang, Q., 2022e. The efficiency and toxicity of dodecafluoro-2-methylpentan-3-one in suppressing lithium-ion battery fire. J. Energy Chem. 65, 532–540. https://doi.org/10.1016/j.jechem.2021.05.043.

Liu, P., Wang, C., Sun, S., Zhao, G., Yu, X., Hu, Y., Mei, W., Jin, K., Wang, Q., 2023. Understanding the influence of the confined cabinet on thermal runaway of large format batteries with different chemistries: a comparison and safety assessment study. J. Energy Storage 74, 109337. https://doi.org/10.1016/j.est.2023.109337.

Liu, C., Liu, Y., Cheng, Z., Li, Y., Liu, P., Liu, L., Min, Y., Duan, Q., Mei, W., Wang, Q., 2025a. Experimental study on the impact of safety valve venting pressure on thermal runaway in large-format lithium iron phosphate battery. Process Saf. Environ. Prot. 201, 107563. https://doi.org/10.1016/j.psep.2025.107563.

Liu, X., Li, Y., Gao, S., Lv, X., Zhou, Z., Wu, W.-T., Wei, L., Lyu, J., Li, Y., Song, Y., 2025b. Suppression thermal runaway propagation of LiFePO4 batteries during nail penetration test based on liquid immersion cooling. Energy 330, 136973. https://doi.org/10.1016/j.energy.2025.136973.

Luo, L., Liu, Y., Liao, Z., Zhong, J., 2023. Optimal structure design and heat transfer characteristic analysis of X-type air-cooled battery thermal management system. J. Energy Storage 67, 107681. https://doi.org/10.1016/j.est.2023.107681.

Maleki, H., Howard, J.N., 2009. Internal short circuit in Li-ion cells. J. Power Sources 191, 568–574. https://doi.org/10.1016/j.jpowsour.2009.02.070.

Mammacıoğlu, O., Coskun, G., 2025. A new experimental approach to lithium-ion battery fires in electric vehicles: investigation of fire behavior and effectiveness of extinguishing agents. Case Stud. Therm. Eng. 73, 106554. https://doi.org/10.1016/j.csite.2025.106554.

Mao, B., Chen, H., Cui, Z., Wu, T., Wang, Q., 2018. Failure mechanism of the lithium ion battery during nail penetration. Int. J. Heat Mass Tran. 122, 1103–1115. https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.036.

Mao, N., Wang, Z., Gao, T., Ouyang, D., Yan, W., 2023. An investigation on thermal runaway behaviours of lithium-ion battery with $Li(Ni_{0.6}Co_{0.2}Mn_{0.2})O_2$ cathode induced by overcharge under different heat dissipation conditions. Int. J. Heat Mass Tran. 217, 124677. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124677.

Mao, B., Yu, S., Zhang, X., Shi, J., Zhang, Y., 2024. Characterization of the deflagration behavior of the lithium-ion battery module within a confined space under different ventilation conditions. Process Saf. Environ. Prot. 184, 1034–1040. https://doi.org/10.1016/j.psep.2024.02.039.

Mei, W., Liu, Z., Wang, C., Wu, C., Liu, Y., Liu, P., Xia, X., Xue, X., Han, X., Sun, J., Xiao, G., Tam, H., Albert, J., Wang, Q., Guo, T., 2023. Operando monitoring of thermal runaway in commercial lithium-ion cells via advanced lab-on-fiber technologies. Nat. Commun. 14 (1), 5251. https://doi.org/10.1038/s41467-023-40995-3.

Meng, X., Yang, K., Zhang, M., Gao, F., Liu, Y., Duan, Q., Wang, Q., 2020. Experimental study on combustion behavior and fire extinguishing of lithium iron phosphate battery. J. Energy Storage 30, 101532. https://doi.org/10.1016/j.est.2020.101532.

Meng, D., Wang, X., Chen, M., Wang, J., 2023. Effects of environmental temperature on the thermal runaway of lithium-ion batteries during charging process. J. Loss Prev. Process. Ind. 83, 105084. https://doi.org/10.1016/j.jlp.2023.105084.

Meng, X., Jiang, L., Duan, Q., Wang, S., Duan, P., Wei, Z., Zhang, L., Jia, Z., Jin, K., Wang, Q., 2023b. Experimental study on exploration of optimum extinguishing agent for 243 Ah lithium iron phosphate battery fires. Process Saf. Environ. Prot. 177, 138–151. https://doi.org/10.1016/j.psep.2023.06.090.

Mishra, D., Shah, K., Jain, A., 2021. Investigation of the impact of radiative shielding by internal partitions walls on propagation of thermal runaway in a matrix of cylindrical Li-Ion cells. J. Electrochem. Soc. 168 (12), 120507. https://doi.org/10.1149/1945-7111/ac3715.

Mohammadi, M.S., Taghilou, M., 2024. Thermal investigation of a lithium-ion cell in presence of PCM within the porous medium considering local thermal nonequilibrium condition. J. Energy Storage 86, 111205. https://doi.org/10.1016/j.est.2024.111205.

National Technical Committee on Road Transport of Standardization Administration of China (SAC/TC 521), 2018. Regulations Concerning Road Transportation of Dangerous Goods. China Communications Press, China.

Nie, B., Dong, Y., Chang, L., 2024. The evolution of thermal runaway parameters of lithium-ion batteries under different abuse conditions: a review. J. Energy Storage 96, 112624. https://doi.org/10.1016/j.est.2024.112624.

Ning, Y., Zhang, Y., Zhu, B., Wei, G., Wang, Q., Qu, J., 2024. Reducing the environmental impact of lithium-ion battery recycling through co-processing of NCM and LFP. Process Saf. Environ. Prot. 187, 810–819. https://doi.org/10.1016/j.psep.2024.05.013.

Parhizi, M., Ahmed, M.B., Jain, A., 2017. Determination of the core temperature of a Li-ion cell during thermal runaway. J. Power Sources 370, 27–35. https://doi.org/10.1016/j.jpowsour.2017.09.086.

Peng, Y., Yang, L., Ju, X., Liao, B., Ye, K., Li, L., Cao, B., Ni, Y., 2020. A comprehensive investigation on the thermal and toxic hazards of large format lithium-ion batteries with $LiFePO_4$ cathode. J. Hazard. Mater. 381, 120916. https://doi.org/10.1016/j.jhazmat.2019.120916.

Peng, R., Kong, D., Ping, P., Wang, G., Gao, X., Lv, H., Zhao, H., He, X., Zhang, Y., Dai, X., 2024. Thermal runaway modeling of lithium-ion batteries at different scales: recent advances and perspectives. Energy Storage Mater. 69, 103417. https://doi.org/10.1016/j.ensm.2024.103417.

Peng, R., Kong, D., Ping, P., Gao, W., Wang, G., Gong, S., Yang, C., Gao, X., He, X., 2025. Experimental investigation of the influence of venting gases on thermal runaway propagation in lithium-ion batteries with enclosed packaging. eTransportation 23, 100388. https://doi.org/10.1016/j.etran.2024.100388.

Perea, A., Paolella, A., Dubé, J., Champagne, D., Mauger, A., Zaghib, K., 2018. State of charge influence on thermal reactions and abuse tests in commercial lithium-ion cells. J. Power Sources 399, 392–397. https://doi.org/10.1016/j.jpowsour.2018.07.112.

Pipeline and Hazardous Materials Safety Administration (PHMSA), 2025. Code of federal regulations. Title 49-Part 173-Surpart E-173 185. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-173/subpart-E/section-173.185.

Qi, X., Liu, B., Pang, J., Yun, F., Wang, R., Cui, Y., Wang, C., Doyle-Davis, K., Xing, C., Fang, S., Quan, W., Li, B., Zhang, Q., Wu, S., Liu, S., Wang, J., Sun, X., 2021. Unveiling micro internal short circuit mechanism in a 60 Ah high-energy-density Li-ion pouch cell. Nano Energy 84, 105908. https://doi.org/10.1016/j.nanoen.2021.105908.

Ren, D., Feng, X., Liu, L., Hsu, H., Lu, L., Wang, L., He, X., Ouyang, M., 2021. Investigating the relationship between internal short circuit and thermal runaway of lithium-ion batteries under thermal abuse condition. Energy Storage Mater. 34, 563–573. https://doi.org/10.1016/j.ensm.2020.10.020.

Ren, Y., Zhang, H., Wei, L., Feng, X., Wu, W., 2024. Multi-layer internal short-circuit mechanism and thermal runaway risk assessment of lithium-ion batteries using nail penetration simulation. J. Energy Storage 97, 112824. https://doi.org/10.1016/j.est.2024.112824.

Sahraei, E., Meier, J., Wierzbicki, T., 2014. Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells. J. Power Sources 247, 503–516. https://doi.org/10.1016/j.jpowsour.2013.08.056.

Santhanagopalan, S., Ramadass, P., Zhang, J., 2009. Analysis of internal short-circuit in a lithium ion cell. J. Power Sources 194, 550–557. https://doi.org/10.1016/j.jpowsour.2009.05.002.

Shen, J., Xu, X., Qian, J., Wen, N., Wang, X., Sun, J., Zhou, F., 2025. Effect of the multilayer heterogeneous fire-retardant composite phase change materials on heat dissipation and preservation performance for lithium-ion battery. J. Energy Storage 119, 116384. https://doi.org/10.1016/j.est.2025.116384.

Song, L., Zhou, Z., Ju, X., Wang, B., Rojas-Alva, U., Zhou, X., Yang, L., 2025. Experimental study on thermal runaway characteristics and fire hazards of lithium-ion batteries in semi-confined space of transportation. J. Energy Storage 128, 117220. https://doi.org/10.1016/j.est.2025.117220.

Sun, J., Ding, H., 2005. Thermal Hazard Assessment of Chemical Substances.

Sun, Q., Wang, H., Xie, S., Jia, J., Chen, X., 2019. Influence of low pressure environment on thermal runaway release temperature of lithium battery. J. Safet. Sci. Technol. 15, 78–83. https://doi.org/10.11731/j.issn.1673-193x.2019.11.012.

Sun, H., Zhang, L., Duan, Q., Wang, S., Sun, S., Sun, J., Wang, Q., 2022a. Experimental study on suppressing thermal runaway propagation of lithium-ion batteries in confined space by various fire extinguishing agents. Process Saf. Environ. Prot. 167, 299–307. https://doi.org/10.1016/j.psep.2022.09.016.

Sun, Q., Liu, H., Zhi, M., Chen, X., Lv, P., He, Y., 2022b. Thermal characteristics of thermal runaway for pouch lithium-ion battery with different state of charges under various ambient pressures. J. Power Sources 527, 231175. https://doi.org/10.1016/j.jpowsour.2022.231175.

Talele, V., Moralı, U., Khaboshan, H.N., Patil, M.S., Panchal, S., Fraser, R., Fowler, M., 2024. Improving battery safety by utilizing composite phase change material to delay the occurrence of thermal runaway event. Int. Commun. Heat Mass Tran. 155, 107527. https://doi.org/10.1016/j.icheatmasstransfer.2024.107527.

Tao, C., Ye, Q., Wang, C., Qian, Y., Wang, C., Zhou, T., Tang, Z., 2020. An experimental investigation on the burning behaviors of lithium ion batteries after different immersion times. J. Clean. Prod. 242, 118539. https://doi.org/10.1016/j.jclepro.2019.118539.

Ubaldi, S., Di Bari, C., Quinterno, M., De Rosa, A., Mazzaro, M., Ferrigno, G., Secci, D., Russo, P., 2024. Suppression capacity and environmental impact of three

extinguishing agents for lithium-ion battery fires. Case Stud. Chem. Environ. Eng. 10, 100810. https://doi.org/10.1016/j.cscee.2024.100810.
United Nations (UN), 2023a. Recommendations on the Transport of Dangerous Doods-Model Regulations-VolumeI, 23 ed. United Nations Publications, New York, NY, USA; Geneva, Switzerland https://unece.org/sites/default/files/2023-08/ST-SG-AC10-1r23e_Vol1_WEB.pdf.
United Nations (UN), 2023b. Recommendations on the Transport of Dangerous Doods-Model Regulations-VolumeII, 23 ed. United Nations Publications, New York, NY, USA; Geneva, Switzerland https://unece.org/sites/default/files/2023-08/ST-SG-AC10-1r23e_Vol2_WEB.pdf.
United Nations (UN), 2023c. Recommendations on the Transport of Dangerous Goods: Manual of Tests and Criteria, 8 ed. United Nations Publications, New York, NY, USA; Geneva, Switzerland https://unece.org/sites/default/files/2024-09/ST_SG_AC.10_11_Rev.8e_WEB.pdf.
United Nations Economic Commission for Europe (UNECE), 2025. ADR 2025-Agreement Concerning the International Carriage of Dangerous Goods by Road. United Nations Publications, New York, NY, USA; Geneva, Switzerland. https://unece.org/adr-2025-files.
Venturelli, M., Broche, L., Buckwell, M., Pfaff, J., Fordham, A., Kirchner-Burles, C., Reid, H.T., Gedara, M., Schopferer, S., Finegan, D.P., Robinson, J., Jervis, R., Rack, A., Darcy, E., Shearing, P., Fransson, M., 2025. Insights into thermal runaway mechanisms: fast tomography analysis of metal agglomerates in lithium-ion batteries. J. Energy Storage 131, 117122. https://doi.org/10.1016/j.est.2025.117122.
Voyiadjis, G.Z., Akbari, E., 2023. Novel procedure to determine the stress-strain relation of lithium-ion batteries through indentation test. Appl. Energy 347, 121492. https://doi.org/10.1016/j.apenergy.2023.121492.
Wang, T., Tseng, K.J., Zhao, J., Wei, Z., 2014. Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies. Appl. Energy 134, 229–238. https://doi.org/10.1016/j.apenergy.2014.08.013.
Wang, H., Du, Z., Liu, L., Zhang, Z., Hao, J., Wang, Q., Wang, S., 2020. Study on the thermal runaway and its propagation of lithium-ion batteries under low pressure. Fire Technol. 56, 2427–2440. https://doi.org/10.1007/s10694-020-00963-5.
Wang, H., Xu, H., Zhang, Z., Wang, Q., Jin, C., Wu, C., Xu, C., Hao, J., Sun, L., Du, Z., Li, Y., Sun, J., Feng, X., 2022. Fire and explosion characteristics of vent gas from lithium-ion batteries after thermal runaway: a comparative study. eTransportation 13, 100190. https://doi.org/10.1016/j.etran.2022.100190.
Wang, G., Kong, D., Ping, P., He, X., Lv, H., Zhao, H., Hong, W., 2023a. Modeling venting behavior of lithium-ion batteries during thermal runaway propagation by coupling CFD and thermal resistance network. Appl. Energy 334, 120660. https://doi.org/10.1016/j.apenergy.2023.120660.
Wang, L., Li, J., Chen, J., Duan, X., Li, B., Li, J., 2023b. Revealing the internal short circuit mechanisms in lithium-ion batteries upon dynamic loading based on multiphysics simulation. Appl. Energy 351, 121790. https://doi.org/10.1016/j.apenergy.2023.121790.
Wang, Z., Zhao, Q., An, W., Shi, B., Li, Z., Liu, H., 2023c. Thermal runaway characteristics of NaCl salt solution-immersed 18650 batteries: impacts of concentration and state of charge. J. Energy Storage 74, 109369. https://doi.org/10.1016/j.est.2023.109369.
Wang, G., Ping, P., Kong, D., Peng, R., He, X., Zhang, Y., Dai, X., Wen, J., 2024a. Advances and challenges in thermal runaway modeling of lithium-ion batteries. Innovation 5 (4), 100624. https://doi.org/10.1016/j.xinn.2024.100624.
Wang, Z., Zhao, Q., Yu, X., An, W., Shi, B., 2024b. Impacts of vibration and cycling on electrochemical characteristics of batteries. J. Power Sources 601, 234274. https://doi.org/10.1016/j.jpowsour.2024.234274.
Wang, J., Li, L., Yu, K., Jia, Y., Zhang, J., Wang, Z., Richard, Y.K.K., Lu, Y., 2025a. Functionalized MXenes nanosheets inspired flame retardant epoxy composites: mechanisms investigation and safety evaluation. Constr. Build. Mater. 464, 140124. https://doi.org/10.1016/j.conbuildmat.2025.140124.
Wang, J., Yang, J., Bai, W., Wang, Z., Yu, K., Lu, Y., Han, C., 2025b. Thermal runaway and jet flame features of LIBs undergone high-rate charge/discharge: an investigation. J. Energy Chem. 103, 826–837. https://doi.org/10.1016/j.jechem.2024.12.004.
Wang, J., Yu, K., Xiao, P., Li, L., Wang, C., Wang, Z., Guo, D., Richard, Y.K.K., Lu, Y., 2025c. Killing two birds with one stone strategy inspired advanced batteries with superior thermal safety: a comprehensive evaluation. Chem. Eng. J. 515, 163272. https://doi.org/10.1016/j.cej.2025.163272.
Wang, Z., Yang, X., Xie, S., 2025d. Study on the thermal safety evolution characteristics and early warning strategies of lithium-ion batteries aged at high-altitude environments. Appl. Therm. Eng. 264, 125501. https://doi.org/10.1016/j.applthermaleng.2025.125501.
Wang, Z., Yu, X., Zhao, Q., Cheng, Q., Shi, B., 2025e. Impact of humidified water mist on thermal runaway characteristics of lithium-ion batteries in a long-narrow confined space. Appl. Therm. Eng. 266, 125636. https://doi.org/10.1016/j.applthermaleng.2025.125636.
Wei, G., Huang, R., Zhang, G., Jiang, B., Zhu, J., Guo, Y., Han, G., Wei, X., Dai, H., 2023. A comprehensive insight into the thermal runaway issues in the view of lithium-ion battery intrinsic safety performance and venting gas explosion hazards. Appl. Energy 349, 121651. https://doi.org/10.1016/j.apenergy.2023.121651.
Xiao, Y., Yang, F., Gao, Z., Liu, M., Wang, J., Kou, Z., Lin, Y., Li, Y., Gao, L., Chen, Y., Ren, S., Li, X., 2023. Review of mechanical abuse related thermal runaway models of lithium-ion batteries at different scales. J. Energy Storage 64, 107145. https://doi.org/10.1016/j.est.2023.107145.
Xie, S., Ren, L., Yang, X., Wang, H., Sun, Q., Chen, X., He, Y., 2020. Influence of cycling aging and ambient pressure on the thermal safety features of lithium-ion battery. J. Power Sources 448, 227425. https://doi.org/10.1016/j.jpowsour.2019.227425.
Xie, S., Wang, Z., Wang, Y., Ren, B., 2025. Thermal safety and risk assessment of lithium-ion batteries aged in low-temperature and low-pressure environments. Appl. Therm. Eng. 279, 127651. https://doi.org/10.1016/j.applthermaleng.2025.127651.
Xu, C., Liu, E., 2025. Battery types – lithium batteries – lithium battery safety | hazards during transport and storage. Encyclop. Electrochem. Power Sourc. 4, 753–759. https://doi.org/10.1016/B978-0-323-96022-9.00302-9. Elsevier.
Xu, J., Liu, B., Hu, D., 2016. State of charge dependent mechanical integrity behavior of 18650 lithium-ion batteries. Sci. Rep. 6, 21829. https://doi.org/10.1038/srep21829.
Xu, J., Guo, P., Duan, Q., Yu, X., Zhang, L., Liu, Y., Wang, Q., 2020. Experimental study of the effectiveness of three kinds of extinguishing agents on suppressing lithium-ion battery fires. Appl. Therm. Eng. 171, 115076. https://doi.org/10.1016/j.applthermaleng.2020.115076.
Xu, J., Duan, Q., Zhang, L., Liu, Y., Zhao, C., Wang, Q., 2022. Experimental study of the cooling effect of water mist on 18650 lithium-ion battery at different initial temperatures. Process Saf. Environ. Prot. 157, 156–166. https://doi.org/10.1016/j.psep.2021.10.034.
Xu, C., Li, Y., Zhang, X., Zhang, Y., Shen, G., Shi, J., Mi, B., 2025. Preparation and characterization of fire-extinguishing efficiency of novel gel foam for lithium-ion battery fires. Process Saf. Environ. Prot. 197, 106999. https://doi.org/10.1016/j.psep.2025.106999.
Yan, J., Wang, Q., Li, K., Sun, J., 2016. Numerical study on the thermal performance of a composite board in battery thermal management system. Appl. Therm. Eng. 106, 131–140. https://doi.org/10.1016/j.applthermaleng.2016.05.187.
Yan, W., Wang, Z., Chen, S., 2021. Quantitative analysis on the heat transfer modes in the process of thermal runaway propagation in lithium-ion battery pack under confined and semi-confined space. Int. J. Heat Mass Tran. 176, 121483. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121483.
Yang, Y., Xu, X., Zhang, Y., Hu, H., Li, C., 2020. Synergy analysis on the heat dissipation performance of a battery pack under air cooling. Ionics 26 (11), 5575–5584. https://doi.org/10.1007/s11581-020-03676-5.
Yang, M., Rong, M., Pan, J., Ye, Y., Yang, A., Chu, J., Yuan, H., Wang, X., 2023. Thermal runaway behavior analysis during overheating for commercial LiFePO4 batteries under various state of charges. Appl. Therm. Eng. 230, 120816. https://doi.org/10.1016/j.applthermaleng.2023.120816.
Yu, T., Wang, Y., Chen, J., Ji, W., Gao, B., Zhu, J., Qin, S., 2025. Applicability of HFC-227ea/CO_2 for battery energy storage systems safety: insights from explosion suppression experiments and kinetic analysis. Int. J. Hydrogen Energy 97, 1424–1439. https://doi.org/10.1016/j.ijhydene.2024.12.022.
Zavalis, T., Behm, M., Lindbergh, G., 2012. Investigation of short-circuit scenarios in a lithium-ion battery cell. J. Electrochem. Soc. 159, A848. https://doi.org/10.1149/2.096206jes.
Zhang, L., Ning, Z., Peng, H., Mu, Z., Sun, C., 2017. Effects of vibration on the electrical performance of lithium-ion cells based on mathematical statistics. Appl. Sci. 7, 802. https://doi.org/10.3390/app7080802.
Zhang, F., Liu, P., He, Y., Li, S., 2022a. Cooling performance optimization of air cooling lithium-ion battery thermal management system based on multiple secondary outlets and baffle. J. Energy Storage 52, 104678. https://doi.org/10.1016/j.est.2022.104678.
Zhang, Q., Niu, J., Yang, J., Liu, T., Bao, F., Wang, Q., 2022b. In-situ explosion limit analysis and hazards research of vent gas from lithium-ion battery thermal runaway. J. Energy Storage 56, 106146. https://doi.org/10.1016/j.est.2022.106146.
Zhang, Q., Niu, J., Zhao, Z., Wang, Q., 2022c. Research on the effect of thermal runaway gas components and explosion limits of lithium-ion batteries under different charge states. J. Energy Storage 45, 103759. https://doi.org/10.1016/j.est.2021.103759.
Zhang, Y., Kong, D., Ping, P., Zhao, H., Dai, X., Chen, X., 2022d. Effect of a plate obstacle on fire behavior of 18650 lithium ion battery: an experimental study. J. Energy Storage 54, 105283. https://doi.org/10.1016/j.est.2022.105283.
Zhang, L., Ye, F., Li, Y., Chen, M., Meng, X., Xu, J., Sun, J., Wang, Q., 2023. Experimental study on the efficiency of dodecafluoro-2-methylpentan-3-one on suppressing large-scale battery module fire. Fire Technol. 59 (3), 1247–1267. https://doi.org/10.1007/s10694-022-01322-2.
Zhang, Y., Zhao, H., Wang, G., Gao, X., Ping, P., Kong, D., Yin, X., 2024. Effect of flame heating on thermal runaway propagation of lithium-ion batteries in confined space. J. Energy Storage 78, 110052. https://doi.org/10.1016/j.est.2023.110052.
Zhang, J., Zhang, H., Xu, S., Yuan, W., Zheng, H., 2025. Role of heat-pipe thermal spreader on the thermal management of light-weight battery module and suppression of thermal runaway. Innov. Energy 2, 100082. https://doi.org/10.59717/j.xinn-energy.2025.100082.
Zhang, J., Long, T., Sun, X., He, L., Yang, J., Wang, J., Wang, Z., Huang, Y., Zhang, L., Zhang, Y., 2026. Mechanism investigation on microstructure degradation and thermal runaway propagation of batteries undergoing high-rate cycling process. J. Energy Chem. 113, 1013–1029. https://doi.org/10.1016/j.jechem.2025.09.074.
Zhao, J., Rao, Z., Li, Y., 2015. Thermal performance of mini-channel liquid cooled cylinder based battery thermal management for cylindrical lithium-ion power battery. Energy Convers. Manag. 103, 157–165. https://doi.org/10.1016/j.enconman.2015.06.056.
Zhao, L., Li, W., Chen, M., 2024. Study on the influence of baffle plate on the thermal runaway propagation of lithium-ion batteries during storage. Appl. Therm. Eng. 253, 123787. https://doi.org/10.1016/j.applthermaleng.2024.123787.
Zhao, H., Tang, X., Li, L., Gong, J., Xiao, Y., 2025. Exothermicity analyses and energy efficiency of a novel liquid cooling strategy in suppressing thermal runaway

propagation of a lithium-ion battery module. Process Saf. Environ. Prot. 201, 07466. https://doi.org/10.1016/j.psep.2025.107466.

Zhou, Z., Zhou, X., Ju, X., Li, M., Cao, B., Yang, L., 2023. Experimental study of thermal runaway propagation along horizontal and vertical directions for LiFePO4 electrical energy storage modules. Renew. Energy 207, 13–26. https://doi.org/10.1016/j.renene.2023.03.004.

Zhu, J., Zhang, X., Sahraei, E., Wierzbicki, T., 2016. Deformation and failure mechanisms of 18650 battery cells under axial compression. J. Power Sources 336, 332–340. https://doi.org/10.1016/j.jpowsour.2016.10.064.

Zhu, J., Zhang, X., Luo, H., Sahraei, E., 2018. Investigation of the deformation mechanisms of lithium-ion battery components using in-situ micro tests. Appl. Energy 224, 251–266. https://doi.org/10.1016/j.apenergy.2018.05.007.

Zhu, F., Zhou, R., Sypeck, D., Deng, J., Bae, C., 2022. Failure behavior of prismatic Li-ion battery cells under abuse loading condition - a combined experimental and computational study. J. Energy Storage 48, 103969. https://doi.org/10.1016/j.est.2022.103969.

Zhu, M., Zhang, S., Chen, Y., Zhao, L., Chen, M., 2023. Experimental and analytical investigation on the thermal runaway propagation characteristics of lithium-ion battery module with NCM pouch cells under various state of charge and spacing. J. Energy Storage 72, 108380. https://doi.org/10.1016/j.est.2023.108380.

Zou, K., Lu, S., 2023. Comparative study on the influence of incident heat flux on thermal runaway fire development of large-format lithium-ion batteries. Process Saf. Environ. Prot. 176, 831–840. https://doi.org/10.1016/j.psep.2023.06.058.