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Ensuring Battery Safety in Electric Vehicles: Challenges, Developments, and Future Perspectives

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With the rapid adoption of electric vehicles (EVs), battery safety has emerged as a cornerstone of innovation in the automotive industry. This review systematically examines critical safety challenges, such as thermal runaway, interfacial degradation, and mechanical abuse, which threaten performance, reliability, and consumer confidence. By bridging material science with systems engineering, it is analyzed failure mechanisms across scales, from atomic-scale dendrite formation to module-level thermal propagation. It is also evaluate advanced diagnostic tools (e.g., machine learning-driven fault detection). Furthermore, emerging solutions is highlighted, such as self-healing electrolytes, nanostructured thermal barriers, and smart battery management systems that enhance resilience while maintaining energy density. This work critically assesses the trade-offs between scalability and safety in next-generation technologies. This review provides a roadmap for researchers and engineers to design highly durable and fail-safe batteries for sustainable transportation by integrating fundamental insights with practical applications.

1. Introduction

The global energy sector remains heavily dependent on fossil fuels, which account for over 80% of worldwide consumption and contribute significantly to environmental pollution and public health crises.[1,2] Electric vehicles (EVs), powered by renewable energy and advanced battery systems, have emerged as a cornerstone of sustainable transportation, offering a pathway to reduce greenhouse gas emissions and reliance on non-renewable resources. This is primarily due to the better energy storage capabilities of batteries.[3] The growth in EVs was significantly aided by increased environmental consciousness, high-energy rechargeable battery research, and regulatory incentives. However, for EVs to compete with internal combustion engine vehicles, they must achieve cost-effectiveness, extended driving ranges, and fast charging goals that hinge on improving battery energy density and safety. The driving range and power output of hybrid electric vehicles (HEVs) and EVs are substantially impacted by the battery type employed as their principal power supply. A variety of battery types have been developed,[4] including lead-acid, nickel-based, sodium-based, and lithium-ion batteries (LIBs). Among them, LIBs are the dominant energy storage technology for EVs due to their high energy density, lightweight design, long cycle life, and rapid charging capabilities.[4,5] Despite these advantages, LIBs face critical safety challenges, including thermal runaway, mechanical/electrical abuse, and chemical degradation, which can lead to catastrophic failures such as fires or explosions. These risks are exacerbated by the industry's pursuit of higher energy densities and aggressive operating conditions, underscoring the need for robust safety protocols to ensure industrial security and public trust.[6] To mitigate these risks, effective maintenance strategies such as Battery Thermal Management Systems (BTMS) which regulate battery temperature using liquid/air cooling or phase-change materials to prevent overheating, and Battery Management Systems (BMS) which monitor real-time parameters (voltage, current, temperature) to balance cell charge/discharge and prevent overcharging/thermal runaway, are essential for safety. Recent advancements in data-driven Prognostics and Health Management (PHM) leverage historical and operational data to model battery degradation patterns, enabling early detection of capacity fade or abnormal behavior. Coupled with machine learning (ML) techniques, these systems analyze vast sensor datasets to predict failures, estimate remaining useful life (RUL), and identify safety hazards like internal short circuits or electrolyte decomposition.[7]

In addition to LIBs, the safety and performance of other battery technologies such as lithium-metal batteries, solid-state batteries, sodium-ion batteries a promising complement to LIBs with successful applications in electric vehicles (EVs), including

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Table 1. Comparison of Battery Technologies for EVs – Key Attributes and Safety Issues.

Battery Type	Pros	Cons	Safety Issues	Remarks
Li-ion[12–15]	High energy density (250–300 Wh kg^{-1}), long cycle life, fast charging	Flammable liquid electrolytes, thermal instability, high cost	Thermal runaway (exothermic reactions), dendrite growth, SEI decomposition, mechanical abuse	Dominant in EVs; safety risks require advanced BMS/BTMS and material innovations
Lead-Acid	Low cost, mature technology, recyclable	Low energy density (30–50 Wh kg^{-1}), short lifespan, heavy	Acid leakage, hydrogen gas emission, limited thermal risks	Obsolete for EVs; used in auxiliary systems
Nickel-Metal Hydride (NiMH)	Moderate energy density (70–100 Wh kg^{-1}), good thermal stability	Memory effect, high self-discharge, toxic components	Overheating under overcharge, hydrogen gas release	Phased out in EVs; limited to hybrid vehicles
Sodium-Ion (Na-ion) [16]	Low cost, abundant materials, better thermal stability	Lower energy density (100–150 Wh kg^{-1}), emerging technology	Limited thermal runaway risk, but structural instability at high voltages	A promising alternative for cost-sensitive markets; safety better than LIBs
Solid-State [17]	Non-flammable solid electrolytes, high energy density (>400 Wh kg^{-1})	High manufacturing cost, interfacial resistance, brittleness	Mechanical failure (cracked ceramics), lithium dendrites in some designs	Emerging tech; intrinsic safety but scalability challenges
Lithium-Metal	Ultra-high energy density (>500 Wh kg^{-1}), fast charging	Severe dendrite growth, electrolyte decomposition	Dendrite-induced short circuits, thermal runaway, poor cycle life	Research focus for next-gen EVs; safety remains a critical bottleneck

Contemporary Amperex Technology Co. Limited's (CATL) lithium-sodium hybrid battery packs and HiNa Battery's sodium-ion projects for heavy-duty trucks,[8,9] and potassium-ion batteries are essential for the growth of EV applications. Each battery type has distinct advantages and unique safety challenges as summarized in **Table 1**. For instance, lithium-metal batteries offer higher energy density but are hindered by dendrite formation, which can lead to internal short circuits and safety hazards. Efforts are ongoing to develop electrolyte additives [10,11] and advanced separators to mitigate these issues. Solid-state batteries, on the other hand, promise enhanced safety by replacing flammable liquid electrolytes with solid alternatives. However, challenges such as mechanical failures in ceramic electrolytes and scalability for mass production need to be addressed. Sodium-ion and potassium-ion batteries, while cost-effective alternatives to LIBs, also face specific safety and performance concerns that need further research.

This review, centers on LIBs, given their dominant role in current EV applications. While the primary focus is on LIBs, the safety strategies and measures discussed are also valuable references for addressing safety concerns across various battery systems.

2. Thermal Runaway and Safety Risks in LIBs

2.1. Operating Principles and Mechanisms of LIBs

Lithium has the largest charge-to-mass ratio of any metal element, making its electrical structure very active. As a result, among battery technologies, LIBs have the highest potential energy density (**Figure 1**).[21] Due to their superior energy storage capabilities, LIBs are widely adopted across various types of EVs. We can categorize EVs into five different types based on their engine technology (HEVs, Fuel Cell Electric Vehicles FCEVs, Plug-in Hybrid Electric Vehicles PHEVs, Battery Electric Vehicles BEVs, and Extended-Range Electric Vehicles ER-EVs).[22] However, their high reactivity and flammable electrolytes pose critical safety risks, such as thermal runaway (triggered by dendrite growth, overcharging, or mechanical damage), fire/explosion hazards from gas venting, and instability under electrical/thermal abuse (e.g., overcharging, overheating).[18–20]

LIB operates chemically as a concentration cell, propelled by the interaction of the electrolyte and electrodes. These batteries use the exchange of lithium ions (Li^+) between the anode and cathode to transform chemical energy into electrical energy.[22] Because of the nanoporous composition of electrodes, Li^+ can intercalate or deintercalate during cycles of charging and discharging. Li^+ ions move directionally across the electrolyte when coupled to an external circuit, creating a closed-loop circuit inside the battery system (**Figure 2a**).

However, the densely packed design of Li-ion cells in EVs introduces additional challenges. These cells are arranged into multiscale structures, including modules and packs, as illustrated in Figure 2b,c. This complex arrangement amplifies the risks of thermal instability. Thermal runaway, a process where structural and thermal degradation within a cell propagates uncontrollably, can occur under certain conditions. The intricate multiscale design makes this phenomenon even more challenging to manage in EV battery systems compared to individual cells.

2.2. Root Causes of Safety Failures

Under normal operation, it is impossible to eliminate the heat generated by the battery, especially on hot days or in larger

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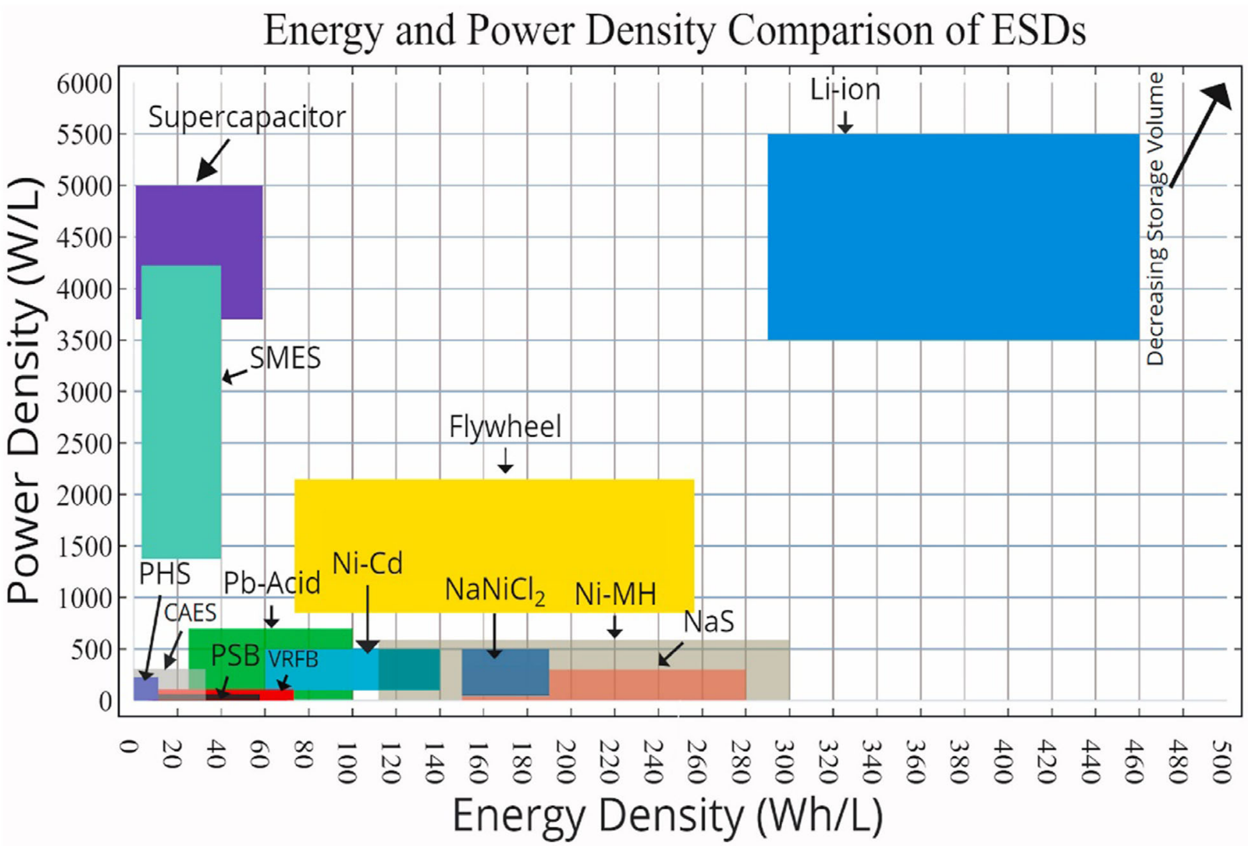

Figure 1. Energy and power density comparison of Energy Storage Devices ESDs. Adapted under terms of the CCBY-NC-ND open access license.[21] Copyright 2022, The Authors, published by Elsevier.

battery packs.[24] The increase in battery temperature has the potential to initiate further undesired parasitic reactions, leading to a phenomenon known as thermal runaway, wherein the generation of heat from the battery becomes uncontrollable.[25] Thermal runaway is more likely to occur during mechanical (such as damage to shell casing, compression, punching, and twisting of cells), electrical (such as overcharge/discharge and short circuit), and thermal (such as thermal shock and local heating) accidents (**Figure 3**).[26–29] Understanding LIB behavior under these extreme conditions is critical for designing intrinsically safer cells through material innovations (e.g., flame-retardant electrolytes) and system-level safeguards (e.g., fail-safe thermal management).

Batteries can experience mechanical damage, thermal abuse, and electrical abuse due to battery accidents, disasters, malfunctions, and inadequate control systems. These factors have the potential to initiate side reactions in battery materials. The primary causes of cell thermal runaway are damaged separators and the release of oxygen from cathodes. This can lead to the production of smoke, flames, and explosions, facilitated by the presence of oxygen from the surrounding air. Collision,[30] charging,[31] and self-ignition[32] are examples of mechanical abuse, electrical abuse, and thermal abuse, respectively. Electric car fires were caused by thermal shock, also known as thermal abuse. The collision process induces compression of the battery, leading to damage in the region experiencing high stress. This damage can result in an internal short-circuit or the rupture of the casing, potentially causing thermal runaway in the batteries. During the process of improper charging, the formation of heat occurs at a delayed stage, preventing its diffusion and causing the accumulation of heat within the battery. This accumulation ultimately leads to the thermal runaway of the batteries. In the course of battery operation, if the heat produced fails to dissipate promptly, it is susceptible to inducing thermal runaway in the battery, which might result in igniting. An electric vehicle fire will trigger the fire of other electric vehicles in the vicinity.

2.2.1. Thermal Runaway Caused by Undesirable Chemical Reactions

A critical component enabling LIB functionality is the solid electrolyte interphase (SEI), a passivation layer formed on the anode surface during initial charging cycles. The SEI is essential because the graphitic anode's low reduction potential would otherwise cause continuous electrolyte decomposition, rendering the battery non-functional. By acting as a lithium-ion conductor (facilitating Li^+ transport) and electronic insulator (preventing further electrolyte reduction), the SEI enables reversible charging and discharging, which is critical for long-term cycling stability. However, the SEI's stability and performance are hindered by its inherent complexity and sensitivity to operating conditions. While the exact formation mechanisms are not fully

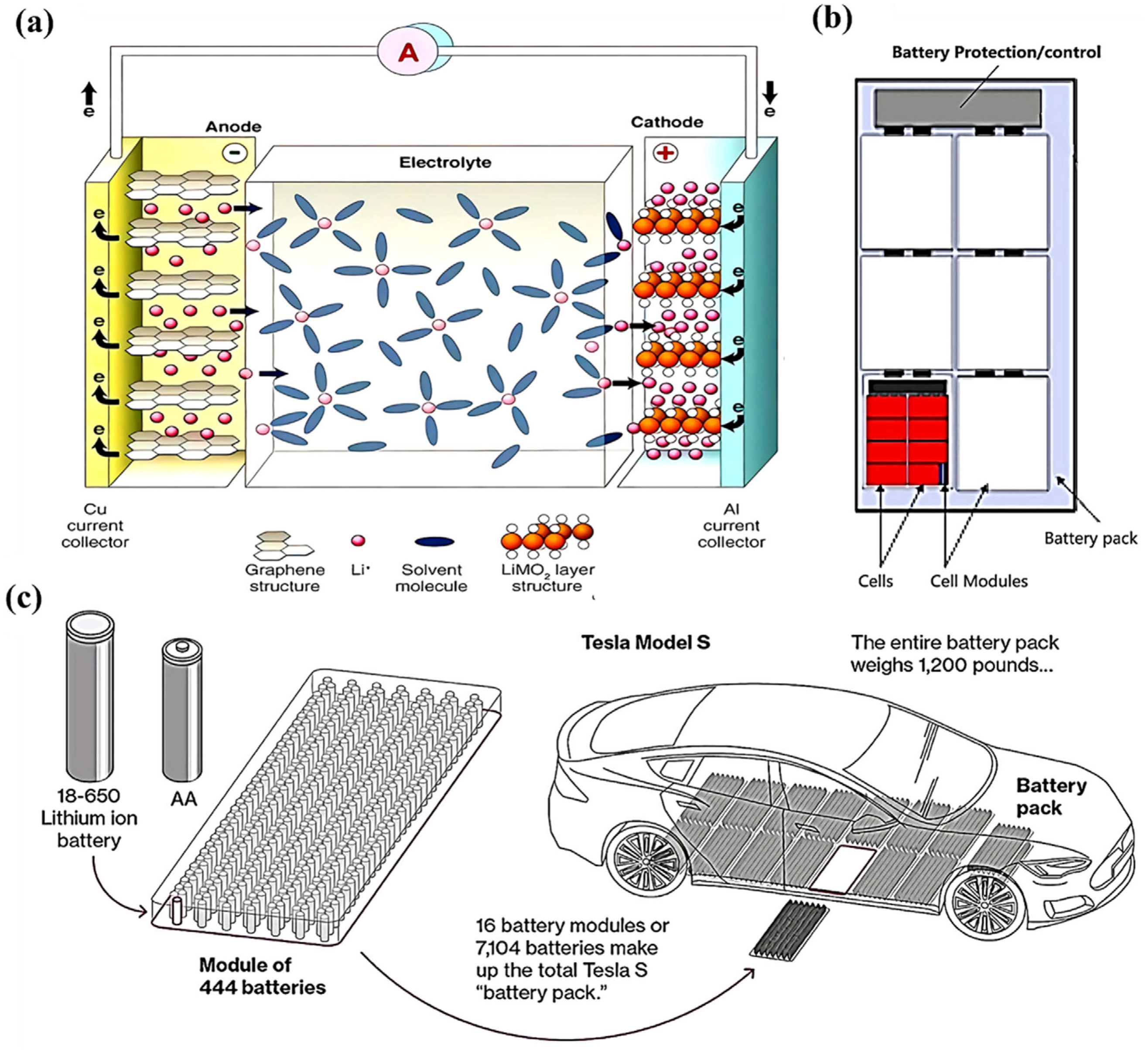

Figure 2. a) Operational mechanism of the Li-ion battery, b) Li-ion battery modules, c) Module of 444 batteries in Tesla Model. Adapted under terms of the CC-BY open access license.[23] Copyright 2021, The Authors, published by John Wiley & Sons.

understood, the SEI arises from the reduction of electrolyte components (solvent, salt, and additives) at the anode surface, creating a heterogeneous layer of organic and inorganic compounds. This complexity poses significant challenges for optimizing SEI properties, particularly for applications like EVs that demand extended cycle life and robust safety.[33–38] Under normal operation, only Li^+ ions shuttle between the cathode and anode at stable voltages and temperatures. At elevated temperatures or voltages, however, electrochemical processes grow unstable, resulting in SEI film disintegration, oxygen release at the cathode side, and parasitic side reactions.[39] SEI layer decomposition and interfacial interactions initially raise the temperature, raising oxygen leak hazards from active cathode materials. Above 80–120 °C, SEI degradation accelerates irreversibly, triggering exothermic reactions (e.g., anode-electrolyte interactions) that outpace heat dissipation.[40] These interactions can produce LIB thermal runaway, resulting in battery rupture and explosion from hot flammable gasses reacting with ambient oxygen.[41]

To contextualize these mechanisms, SEI degradation increases cell impedance, leading to localized Joule heating.[39–41] This heat propagates to the cathode, accelerating delithiation and lattice oxygen release (e.g., in NMC cathodes). Additionally, dissolved transition metals from the cathode (e.g., Mn^{2+}) may migrate to the anode, destabilizing the SEI further through the catalytic decomposition of the electrolyte.[41] Two interrelated pathways mediate these processes:

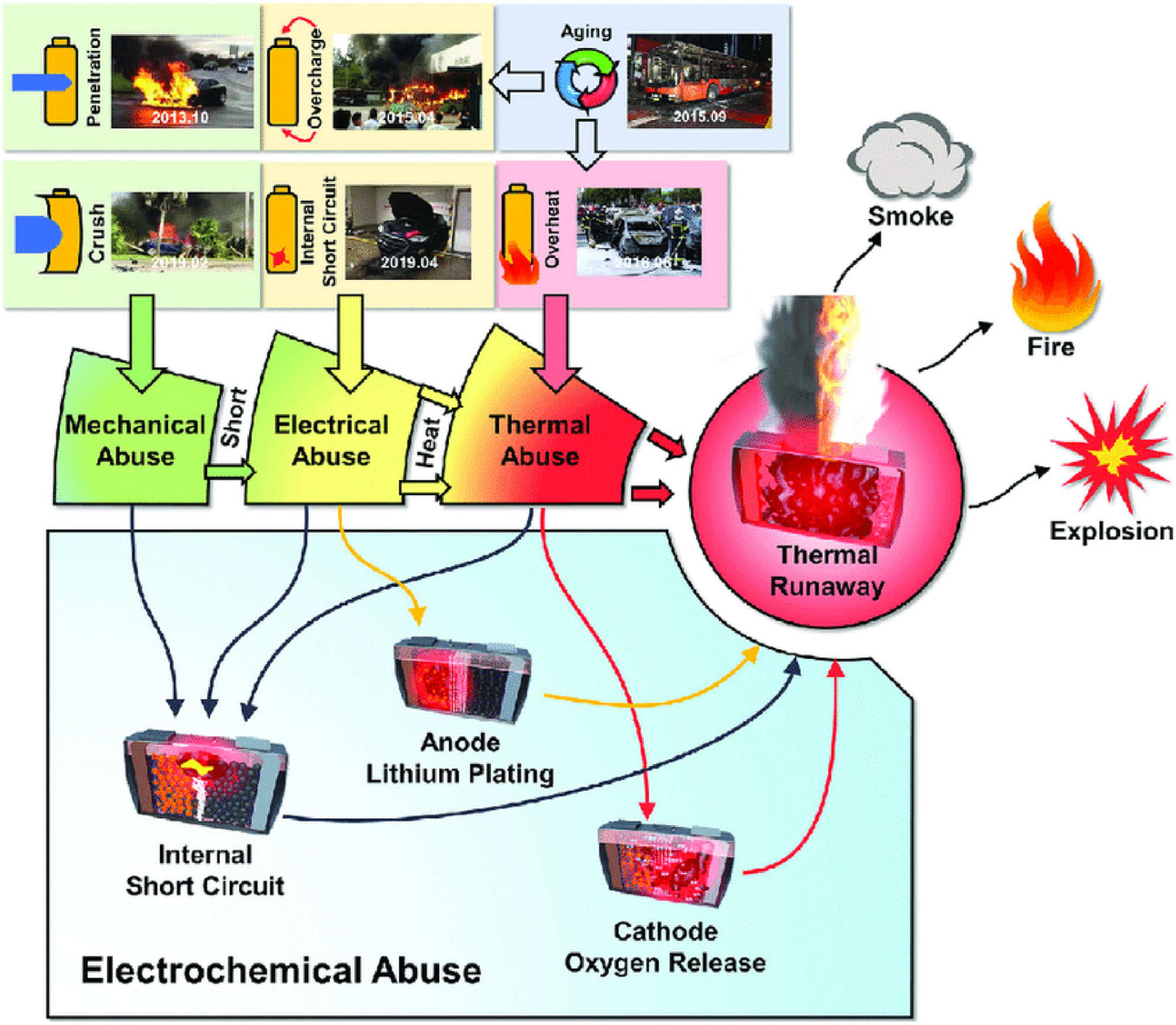

Figure 3. A comprehensive examination of battery safety concerns. Adapted under terms of the CC-BY-NC-ND open access license.[29] Copyright 2020, The Authors, published by Elsevier.

First, thermal/mechanical coupling drives failure propagation: SEI failure at the anode triggers localized heat generation and mechanical stress, which accelerates cathode delamination or structural cracks. This destabilizes the cathode lattice, promoting oxygen release and exacerbating exothermic reactions. Second, electrolyte oxidation plays a critical role: SEI breakdown exposes the anode to fresh electrolytes, increasing parasitic oxidation reactions. Reactive oxygen species (e.g., O^- radicals) generated at the anode migrate to the cathode, further destabilizing its structure and exacerbating oxygen evolution during cycling. Together, these pathways create a feedback loop that amplifies thermal runaway risks, underscoring the need for multi-faceted mitigation strategies.

Understanding and controlling SEI formation and degradation are therefore critical for advancing LIB technology (Table 2), ensuring safe and efficient operation in next-generation energy storage systems. To this end, machine learning (ML) has emerged as a transformative tool for SEI control, leveraging multimodal datasets to predict and optimize interfacial stability. These models are trained on in situ/operando spectroscopy data (e.g., Raman, Fourier-Transform Infrared Spectroscopy (FTIR), X-ray Photoelectron Spectroscopy (XPS)) to track SEI composition and thickness evolution, combined with electrochemical cycling metrics such as voltage profiles, capacity fade rates, and impedance spectra. Operational parameters like temperature, pressure, and electrolyte formulations are also integrated to capture SEI behavior under diverse conditions. To address the dynamic nature of SEI evolution, time-series architectures (e.g., Long Short-Term Memory networks (LSTMs), Recurrent Neural Networks (RNNs)) correlate transient electrochemical states with degradation patterns, while physics-informed hybrid models embed diffusion-reaction kinetics to constrain predictions within thermodynamic limits. Transfer learning further refines these models by fine-tuning accelerated aging data with real-time

Table 2. SEI Formation, Degradation, and Control Strategies.

Aspect	SEI Formation	SEI Degradation	Strategies for Control
Mechanism	Forms during initial cycles via electrolyte reduction (e.g., EC, $LiPF_6$ decomposition).	Degrades due to mechanical stress, thermal instability, or anode volume changes.	**Electrolyte Additives** (e.g., VC, FEC): Stabilize SEI by forming LiF/Li_2CO_3-rich layers.
Role/Impact	- Prevents electrolyte decomposition. - Enables Li^+ transport. - Blocks electrons.	- Causes capacity fade. - Increases impedance. - Promotes dendrite growth.	**Artificial SEI Layers** (e.g., LiF, Li_3PO_4 coatings): Enhance mechanical/chemical stability.
Key Challenges	Achieving uniform thickness and ionically conductive SEI.	Dynamic SEI repair consumes Li^+ and electrolytes, accelerating capacity loss.	**Advanced Characterization** (XPS, AFM, cryo-EM): Monitor SEI evolution in real-time.
Technical Solutions	- Optimizing electrolyte composition. - Pre-lithiation techniques.	- Self-healing polymers. - Hybrid electrolytes (organic-inorganic).	**Machine Learning**: Predict optimal SEI-forming conditions via data-driven models.
Benefits of Control	- Longer cycle life. - Higher Coulombic efficiency. - Improved safety.	- Reduced capacity fade. - Delayed thermal runaway. - Enhanced rate capability.	**Dual-Salt Electrolytes** (e.g., $LiDFOB/LiBF_4$): Synergistically stabilize SEI/CEI layers

cycling inputs, enabling adaptive protocols that enhance SEI resilience.

2.2.2. Thermal Runaway Caused by Mechanical Abuse

Mechanical impacts, such as collisions or penetration, can cause localized damage to LIBs, leading to significant heat generation. Penetration, in particular, represents an extreme mechanical abuse scenario where foreign objects (e.g., road debris, sharp structures) pierce the battery structure. Unlike gradual crush conditions, penetration can instantaneously trigger fierce internal short circuits due to direct electrode-separator compromise, accelerating thermal runaway initiation. This process is depicted in **Figure 4**, where the stages of mechanical abuse are shown alongside the corresponding force, voltage, and temperature profiles. As illustrated, the progression from Stage I to Stage IV involves an increase in force (Stage I), the onset of thermal instability (Stage II), significant heat release (Stage III), and eventual structural failure (Stage IV).

Such heat generation can trigger thermal runaway, a critical failure mode in LIBs, where uncontrolled temperature rises, causing catastrophic outcomes. With the increasing prevalence of EVs equipped with LIBs, concerns about battery safety during vehicle crashes have gained significant attention. Research has extensively analyzed the behavior of LIBs under mechanical abuse, as well as the resulting safety implications.[39,42,43] These studies provide critical insights for developing safer battery systems to mitigate risks in real-world scenarios.

Real-world examples of these risks are documented in references [43] and [44] including incidents where collisions led to battery ignition, occupant entrapment, fatalities, and persistent thermal runaway. These cases align with findings from a 2020 National Transportation Safety Board (NTSB) report highlighting responder risks during high-voltage LIB fires.[45] Collectively, they underscore the critical need for improved safety measures such as enhanced crash-resistant battery designs, advanced thermal management systems, and specialized emergency response protocols for EV fires.

To contextualize these examples, mechanical abuse in LIBs encompasses both crush and penetration events. While gradual crushing allows partial heat dissipation, penetration induces immediate internal short circuits due to a direct physical breach of the battery structure. Both pathways accelerate thermal runaway, but penetration poses unique challenges due to its abrupt onset and localized energy release. Mitigation strategies must address these distinct failure modes through robust mechanical protection (e.g., reinforced housings), separator integrity enhancements, and real-time fault detection systems.

2.2.3. Thermal Runaway Induced by Electrical Abuse

When a battery is in a state of excessive charging or discharging or is enduring an external short circuit, it undergoes electrical abuse, leading to a sequence of unfavorable electrochemical processes. Battery overcharging (**Figure 5**) can be attributed to various factors. One of the important factors is the lack of consistency in battery cells. If the management system is unable to efficiently monitor the voltage of any battery cell, there is a potential risk of overcharging. Overcharging poses a significant risk due to the storage of surplus energy in the battery. In general, batteries are initially charged to a predetermined state of charge (SOC), although certain batteries may possess a greater SOC prior to the charging process. Consequently, if these batteries are subjected to additional charging, they will experience overcharging.[46] The initial consequence of overcharge is the breakdown of the electrolyte at contact with the cathode.[47] This process gradually elevates the temperature of the battery. Following this, there is an excessive deintercalation of Li^+ ions from the cathode. The cathode material undergoes instability and initiates the release of oxygen, while an excessive amount of Li^+ ions accumulate on the anode, resulting in the formation of Li dendrite.[48] Safety issues, such as cell overheating, short circuits, and rupture, can occur

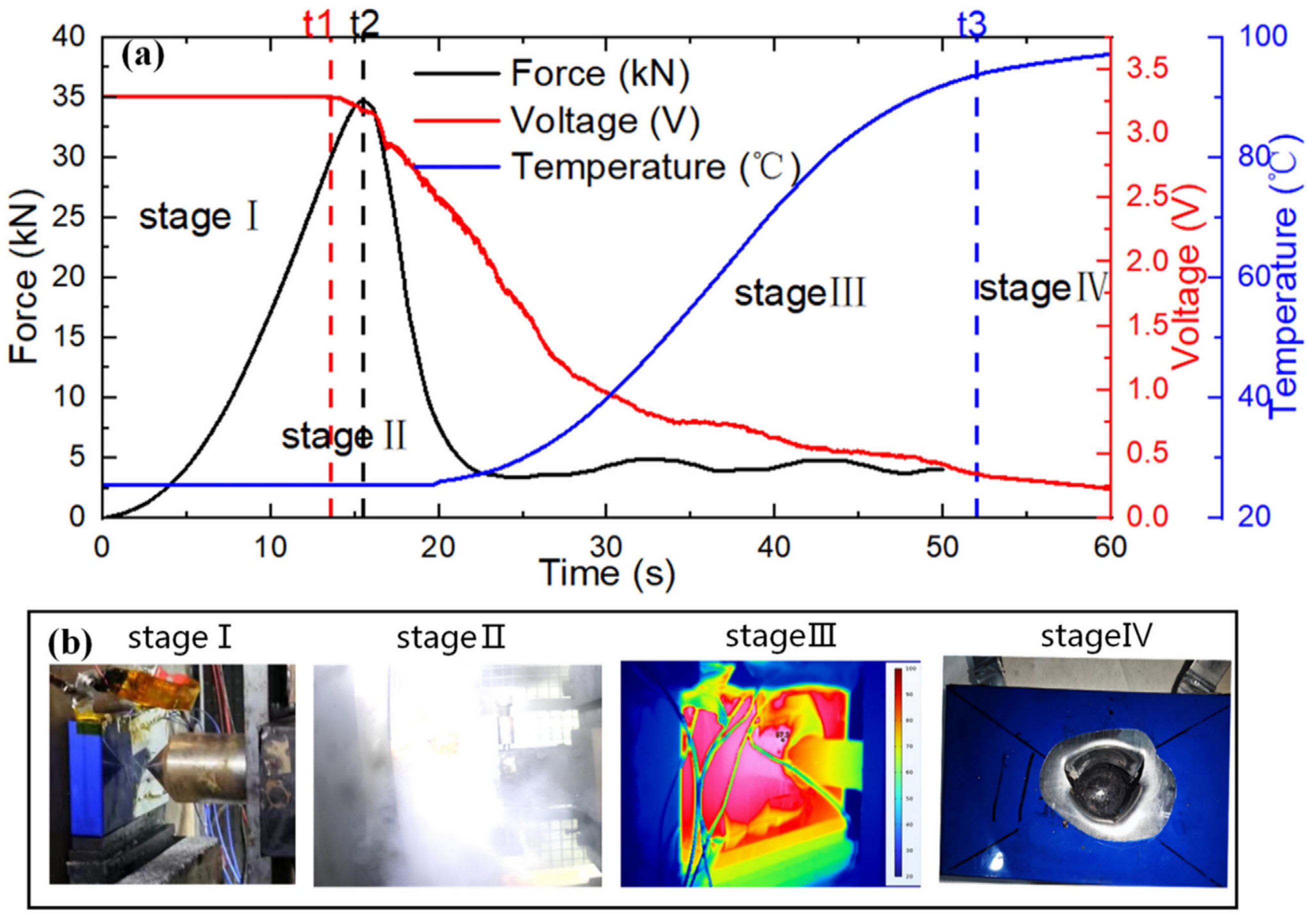

Figure 4. a) mechanical-electrical-thermal response curve, b) Infrared and digital photos of $LiFePO_4$ (LFP) cells throughout tests. Adapted under terms of the CC-BY open access license.[39] Copyright 2024, The Authors, published by Springer Nature.

due to the creation of heat, dendrite, and gas during electric abuse.[49]

There is a similarity between the principle of over-discharge (**Figure 6**) and over-charge. Certain cells attain the predetermined state of discharge (SOD) ahead of time. Therefore, an over-discharge phenomenon arises when a cell is compelled to sustain its discharge process.[51] The continual release of Li^+ from the anode caused by forced over-discharge alters the structure of graphite and leads to the destruction of the SEI. At a significant depth of SOD, the copper current collector undergoes oxidation, resulting in the possible deposition of copper ions onto the surface of the cathode.[52] Excessive deposition of copper leads to the occurrence of a short circuit within the cell.

When the positive cathode and the negative anode of a single cell make direct contact via a conductor, an external short circuit takes place. In such instances, rather than having separate electron and ion transportation, both electron and ion transfer take place simultaneously, resulting in the rapid migration of Li^+ ions within the cell, leading to the rapid discharge of the battery. In the event of a safety incident, it is possible for a LIB cathode and anode to make contact, resulting in the rapid and uniform release of heat.[53]

Among the three electrical abuses, overcharging is the most prevalent cause of LIB safety incidents and one of the most hazardous forms of electrical misuse. The external short circuits and over-discharge are comparatively innocuous and do not result in immediate and rapidly developing catastrophes. However, it is critical to note that while overcharging poses the most severe immediate risk due to rapid cathode decomposition and oxygen release, external short circuits and over-discharge still present significant safety concerns. External short circuits generate heat through Joule heating, but in practical battery systems, this heat often dissipates gradually, delaying thermal runaway initiation. However, in some cases, high peak currents during external short circuits can induce rapid temperature rises exceeding 132 °C (separator shutdown threshold) and cell swelling due to gas generation (e.g., CO, CH_4, H_2) from electrolyte decomposition and electrode reactions. Leising et al. (2001) demonstrated through internal thermocouple measurements that while cells may remain hermetically sealed during short circuits, they still reach critical internal temperatures.[54] Larsson and Mellander (2014) further showed that even modest external heating can trigger thermal runaway with temperatures exceeding 700 °C in cobalt-based systems.[53] The generated gases form flammable and explosive mixtures (e.g., ethylene, propylene), exacerbating fire risks. Xu et al. (2024) quantified gas production during thermal runaway, revealing up to 17.48 mol of combustible gases in NCM622 systems at full SOC, with ethylene concentrations

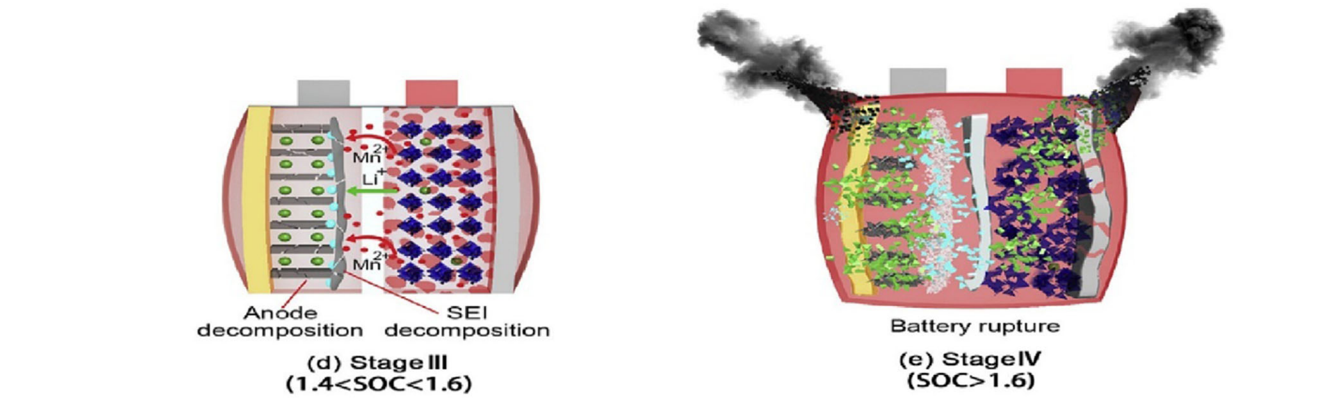

Figure 5. A diagrammatic illustration of the overcharge. Adapted under terms of the CC-BY open access license.[50] Copyright 2023, The Authors, published by Elsevier.

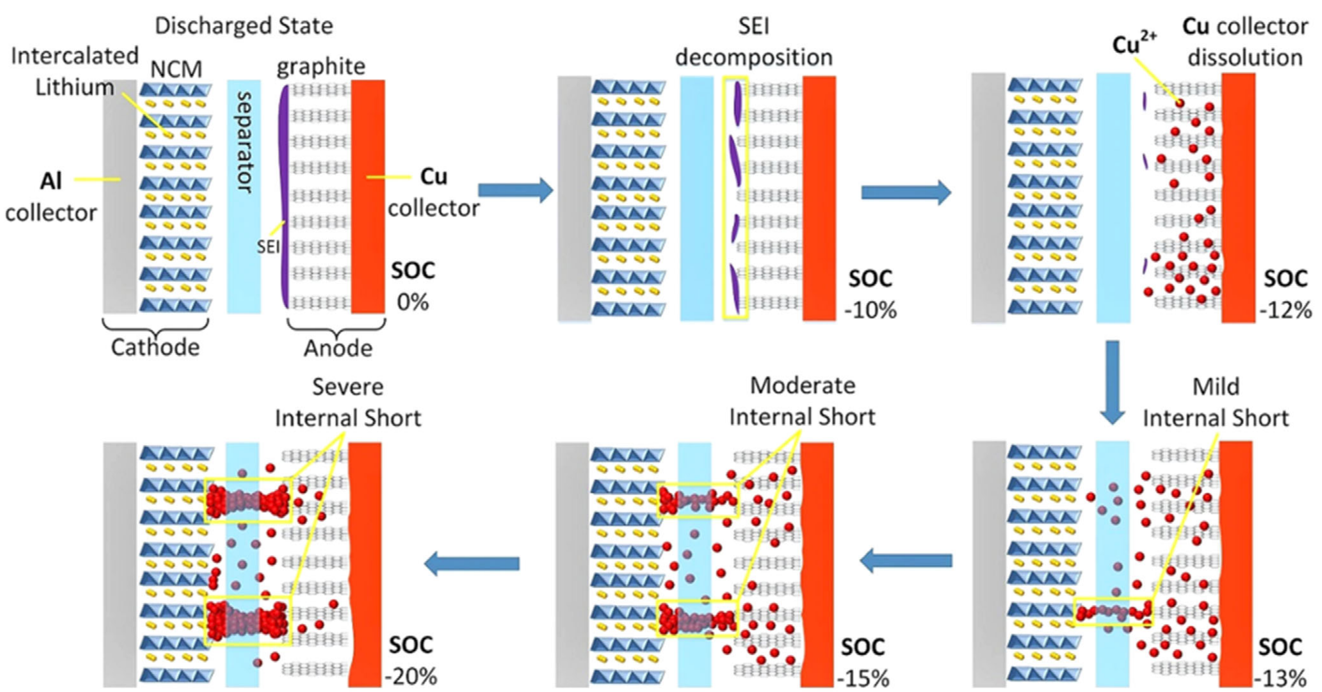

Figure 6. A diagrammatic illustration of the over-discharge. Adapted under terms of the CC-BY open access license.[57] Copyright 2016, The Authors, published by Springer Nature.

Table 3. Temperature ranges of various exothermic reactions occurring in LIBs.

Reactions	Temperatures range °C	Impact on Battery Performance/Safety	Refs.
LiC_6/electrolyte	110–290	Leads to SEI breakdown, gas generation, and thermal runaway.	[63]
Li_xCoO_2decomposition	178–250	Oxygen release accelerates electrolyte oxidation, increasing fire risk	[65]
SEI decomposition	100–130	Exposes fresh anode to the electrolyte, causing further decomposition and capacity	[62]
LiC_6/PVDF	220–400	Produces toxic gases (e.g., HF) and damages electrode integrity.	[64]
$Li_xNi_{0.8}Co_{0.2}O_2$ decomposition	175–340	Releases oxygen, leading to electrolyte combustion and thermal runaway.	[66]
Li_xCoO_2/Electrolyte	167–300	Generates heat and gases, increasing internal pressure and risk of explosion.	[67]
$Li_xNi_{0.8}Co_{0.2}O_2$/Electrolyte	180–230	Causes rapid heat generation and gas evolution, escalating thermal runaway.	[68]
Electrolyte decomposition	225–300	Produces flammable gases (e.g., CO, CH_4) and accelerates thermal runaway.	[69]

posing particular explosion hazards.[55] Wang et al. (2022) comparatively analyzed vent gases from different chemistries, finding unexpectedly higher explosion risks in $LiFePO_4$ systems despite their thermal stability.[56] Importantly, both abuse conditions necessitate rigorous monitoring in battery management systems to prevent cascading failures.

2.2.4. Thermal Runaway Caused by Thermal Abuse

A battery may endure thermal shock or high temperatures in thermal abuse settings.[58] EV charging and neighboring vehicle fires might cause battery fires. Combustibles in the air, such as flying seeds, flowers, or leaves, can ignite near a malfunctioning battery or spark, causing surrounding fires.

If the heat produced during regular LIB operations is not rapidly released, the separator in that particular location will contract or break. Consequently, a portion of the thermal energy is retained within the battery. Once a certain threshold is reached, if the heat persists in accumulating rather than being released, exothermic side processes commence, hence intensifying thermal stress.[59] The temperature ranges of the typical exothermic reactions occurring in LIBs are presented in **Table 3**.[60–69] The explosion is caused by thermal stress and pressure build-up resulting from the release of volatile side-products during parasitic processes.

2.3. Thermal Runaway: Mechanisms and Propagation

The most harmful safety concern for LIBs is thermal runaway. There has been a notable increase in the focus on safety within the realm of battery design. Under circumstances of improper usage, batteries have the potential to undergo thermal runaway. The onset of this condition can be initiated by an increase in temperature. In such situations, the excessive dissipation of thermal energy has the potential to cause damage to the battery cell, hence increasing the risk of fires or even explosions. It is imperative to comprehend that thermal runaway reactions exhibit a high degree of complexity and exhibit significant variations depending on the materials under consideration. Thermal runaway is initiated by methods involving mechanical, electrical, and thermal abuse.[70]

Figure 3 illustrates the sources of thermal runaway in batteries, encompassing the influence of electrolyte side reactions, cathode and anode reactions, as well as interfacial reactions occurring at the electrode surface and Li plating.[76,77] Li plating, the deposition of metallic lithium on the anode surface, is a critical factor that significantly impacts battery safety and longevity. This phenomenon often occurs during overcharging or operation at low temperatures, leading to the formation of lithium dendrites. These dendrites can penetrate the separator, causing internal short circuits and heightening the risk of thermal runaway. There exist four primary categories of causes underlying thermal runaway in LIBs, as depicted in Figure 3. The first category, thermal abuse, involves the uncontrollable generation of internal heat, which leads to the release of oxygen from the cathode material and initiates a cascade of side reactions.[71,72] Consequently, the stored energy is rapidly dissipated, resulting in unwanted chemical chain reactions and the emission of substantial quantities of heat.[73] The second category, electrical abuse, occurs during overcharging or high states of charge (SOC), where electrolyte decomposition at the cathode-electrolyte interface generates heat, causing oxygen release and potential separator damage.[74] The third category, electrochemical abuse, arises from localized thermal distress during normal LIB operation. If the heat generated cannot be effectively dissipated, the separator in the affected area may shrink or rupture, leading to internal short circuits and further thermal escalation.[18,75] The fourth category, mechanical abuse, results from physical damage such as crushing or puncturing, which can cause separator failure, internal short circuits, or air infiltration into the battery, all of which can trigger thermal runaway.[43] Among these categories, the primary factors contributing to battery safety incidents are short-circuiting due to separator damage, electrical abuse, and mechanical abuse, highlighting the critical need for robust safety measures in LIB design and operation.

It is widely recognized that the performance and safety of LIBs are closely correlated with their operating temperature. The optimal operational temperature for these batteries typically falls between 15 and 35 °C, as shown in **Figure 7**.[78] However, the ideal temperature range for battery operation generally spans from ≈25 to 45 °C, with minor variations depending on the specific battery type and design. If the temperature surpasses this permissible range during charging or discharging, the routine operation of the batteries may be compromised. Additionally, the temperature differential between interconnected LIB cells within a battery module or pack must not exceed 5 °C to maintain uniform performance and safety.[79–82]

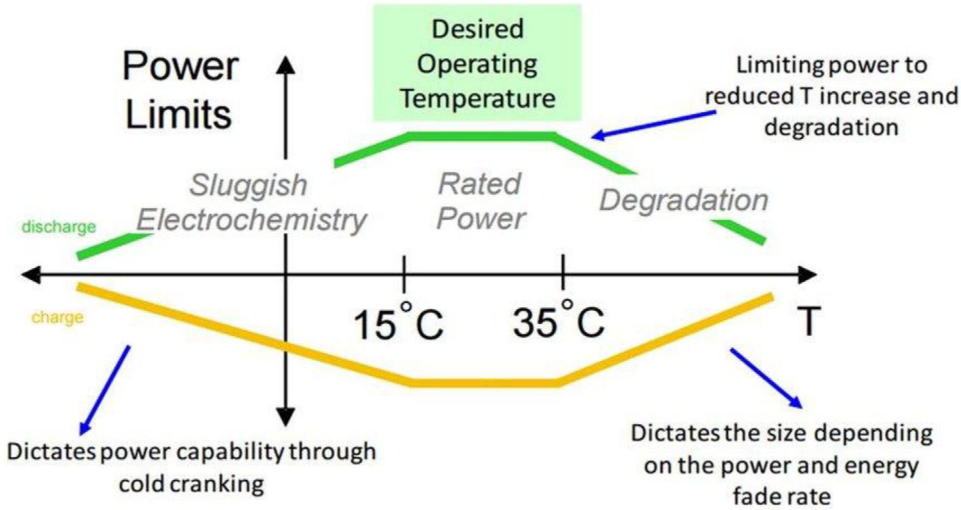

Figure 7. Correlation between operating temperature and battery performance. Adapted under terms of the CC-BY open access license.[78] Copyright 2023, The Authors, published by Springer.

Numerous reviews have thoroughly examined the thermal runaway mechanism.[25,83–87] The scholarly community has agreed on the path of each step, despite disagreements over the specifics and time points of the reaction. Capacity degradation, breakdown of the passivation layer, reactions between the electrolyte and cathode, separator failure, cathode decomposition, electrolyte breakdown, interactions between the binder and cathode, and electrolyte combustion are the eight key mechanisms driving thermal runaway across low to high temperatures.[88] The internal environment of the battery is constantly changing due to heat deposition and accumulated reaction products. Battery overheating and short circuits are eventually caused by worsened structural degradation.[89] When temperatures increase to a range of 60 to 80 °C, the battery is susceptible to electrochemical degradation. The SEI undergoes decomposition, leading to potential unfavorable reactions between the anode and cathode materials and the electrolyte. The aforementioned processes, in conjunction with the collapse of the separator, result in the degradation of the electrolyte and the generation of combustible hydrocarbons, hence exacerbating the generation of heat at temperatures ranging from 100 to 200 °C. Thermal runaway occurs when temperatures are beyond critical thresholds, often ranging from 220 to 260 °C, resulting in a significant increase in temperatures exceeding 800 °C (**Figure 8**). The swift increase in voltage compels the battery to abruptly dissipate its accumulated energy. Critically, thermal runaway is invariably accompanied by substantial gas generation (CO, CH_4, H_2, C_2H_4) that profoundly influences its progression. As previously noted, these gases form explosive mixtures that accelerate combustion and cell rupture. Gas composition directly reflects failure mechanisms: electrolyte decomposition produces CO/light hydrocarbons,[55] while cathode degradation releases oxygen (as demonstrated in cobalt-based systems).[53] Quantitatively, Xu et al.[55] measured up to 17.48 mol of gas in NCM622 cells, with ethylene (C_2H_4) concentrations posing severe explosion hazards. Notably, Wang et al.[56] confirmed even thermally stable $LiFePO_4$ generates hazardous gas mixtures (dominant CO/H_2), underscoring universal risks. Reverse analysis of such gas signatures thus provides critical diagnostic insights into runaway triggers. The ultimate phase of this perilous procedure may culminate in a fire or explosion, wherein the battery becomes ignited and the subsequent reaction has the potential to trigger a cascade of malfunctions in neighboring cells within the battery pack.

3. Battery Failure Types, Maintenance, and Safety Solutions

3.1. Battery Failure Types

LIB systems primarily consist of cells, a BMS, sensors, and connection components. The intricate internal operational mechanisms, coupled with diverse external user conditions, result in various fault types and complex fault evolution patterns. From a control system perspective, faults in LIB systems can be categorized into two principal types: cell faults and system faults (**Figure 9**). Cell faults, which play a critical role in determining battery system safety, are further subdivided into progressive faults[91–96] and sudden faults.[97–103] Progressive faults develop gradually and include mechanisms such as lithium plating and dendrite growth (Figure 9a), loss of active material (LAM) at the anode and cathode (Figure 9b), resistance increment (Figure 9c), electrolyte consumption (Figure 9d), particle cracking (figure 9e), current collector corrosion (Figure 9f), and SEI thickening (Figure 9g). These degradation modes collectively impair long-term performance and safety. In contrast, sudden faults occur abruptly and include catastrophic events like thermal runaway, capacity diving, and internal short circuits, which often lead to immediate system failure if unmitigated. System faults encompass issues external to the cell, such as BMS errors, sensor malfunctions (e.g., inaccurate voltage/temperature readings), and connection component failures (e.g., loose terminals or module-level disconnections). This subsection provides a detailed

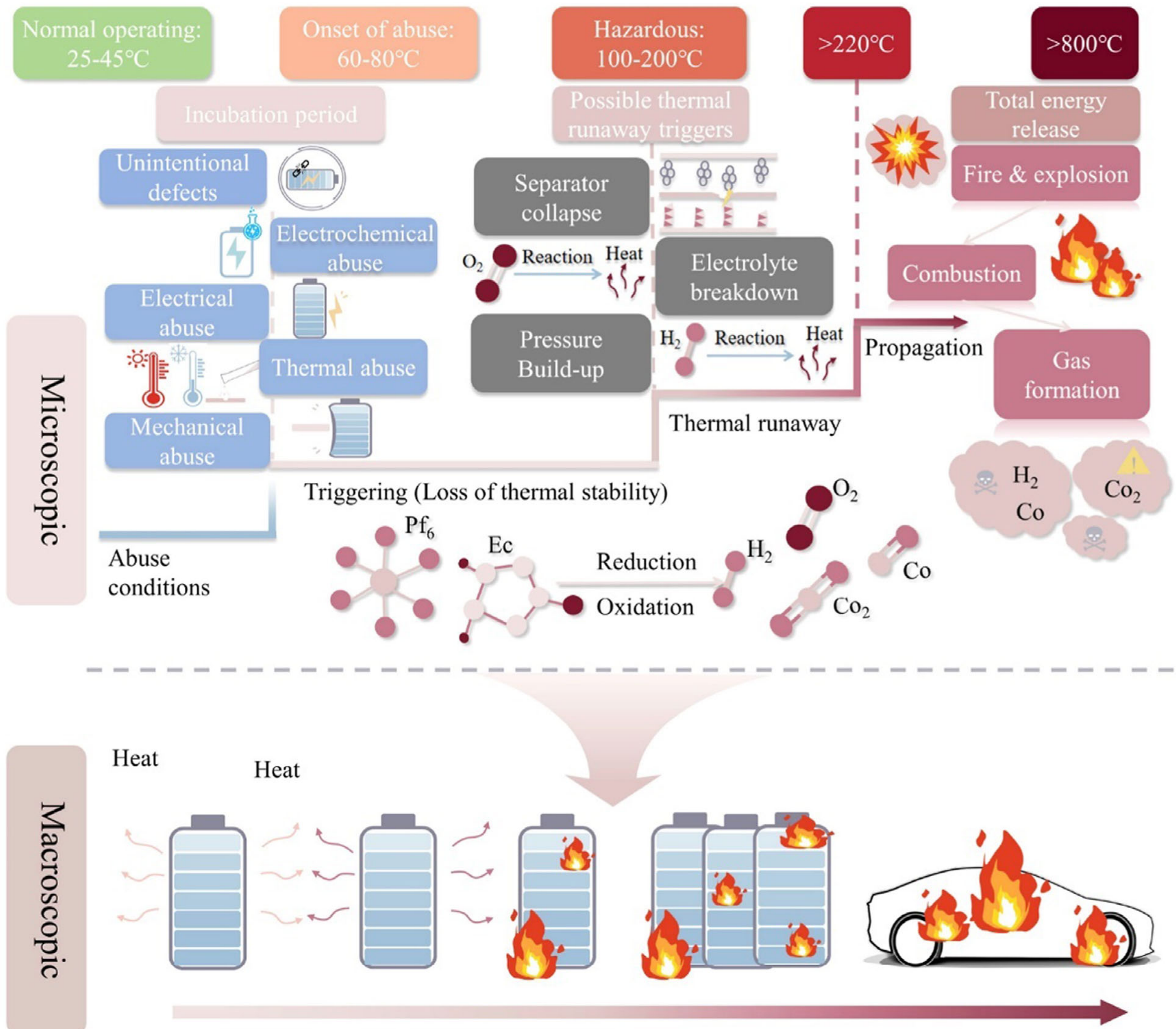

Figure 8. Thermal runaway propagation. Adapted under terms of the CC-BY-NC-ND open access license.[90] Copyright 2024, The Authors, published by Elsevier.

examination of these fault types, emphasizing their root causes progression pathways, and implications for LIB system reliability.

When a battery is subjected to excessive stress or improper use beyond its design limits, a series of chemical reactions are initiated within the cell. These reactions mark the onset of a complex chain of events that can compromise battery integrity. Under extreme operating conditions, the primary battery components, the anode, cathode, separator, electrolyte, and current collectors, undergo complex and often undesirable reactions. This interaction results in a highly intricate system of physicochemical processes, governed by kinetic and thermodynamic principles, which evolve dynamically as the stress increases. Three critical factors temperature, SOC, and current rate are three pivotal factors that significantly influence these processes. They determine the intensity and progression of chemical reactions within the cell. The electrochemical effects of these conditions can be categorized into four distinct groups, as depicted in **Figure 10**. Each category corresponds to specific phenomena occurring within the cell, providing insights into the mechanisms and consequences of battery abuse.

1) An internal short circuit because the separator failed (**Figure 11c**).[104]
2) When lithium deposits form on the anode surface, they react with the electrolyte, leading to undesirable chemical interactions.[105]
3) Parasitic side reactions degrade battery capacity by damaging the SEI and promoting its uncontrolled growth.[106]
4) Batteries reach their end of life (EOL) when intrinsic degradation mechanisms reduce capacity to 80% of its initial value, marking the limit of operational viability.
5) Oxygen released from the cathode during decomposition reacts with the anode, producing substantial heat and exacerbating thermal instability.[107,108]

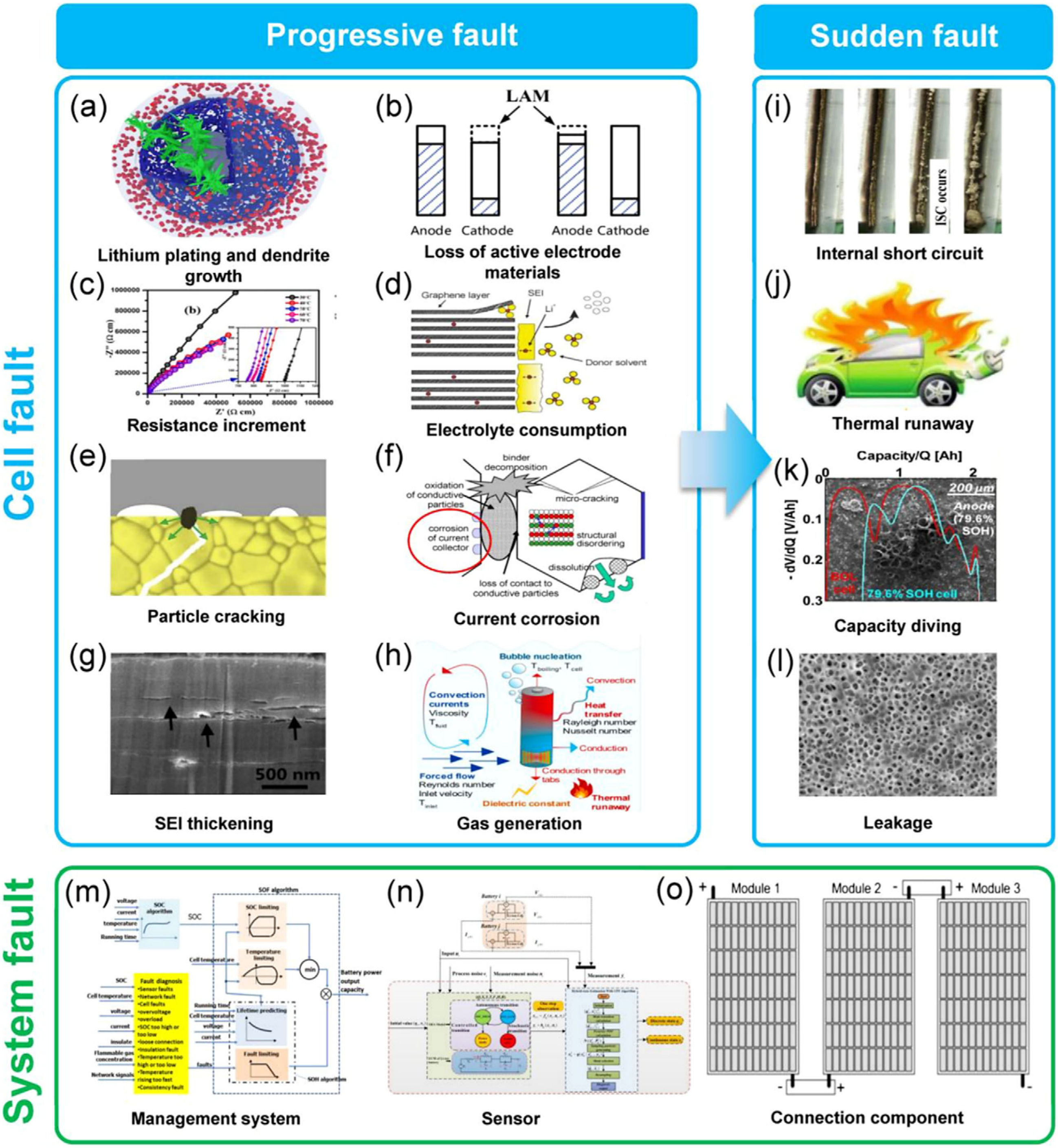

Figure 9. Cell faults: a) 3D schematic of Li deposition. b) Active electrode material consumption. c) Impedance profiles of batteries. d) Electrolyte consumption at the anode/electrolyte interface. e) Mechanical failure of ceramic electrolytes. f) Corrosion of cathode materials. g) Cross-sectional image showing SEI thickening. h) Gas generation modeling. i) Lithium dendrite-induced internal short circuits. j) Thermal runaway incidents. k) Cell capacity loss. l) SEM images of porous membranes. System faults: m) Battery state estimation algorithm framework. n) Fault diagnosis of sensors. o) Battery component connection faults. Reproduced under terms of the CC-BY open access license.[107] Copyright 2023, The Authors.

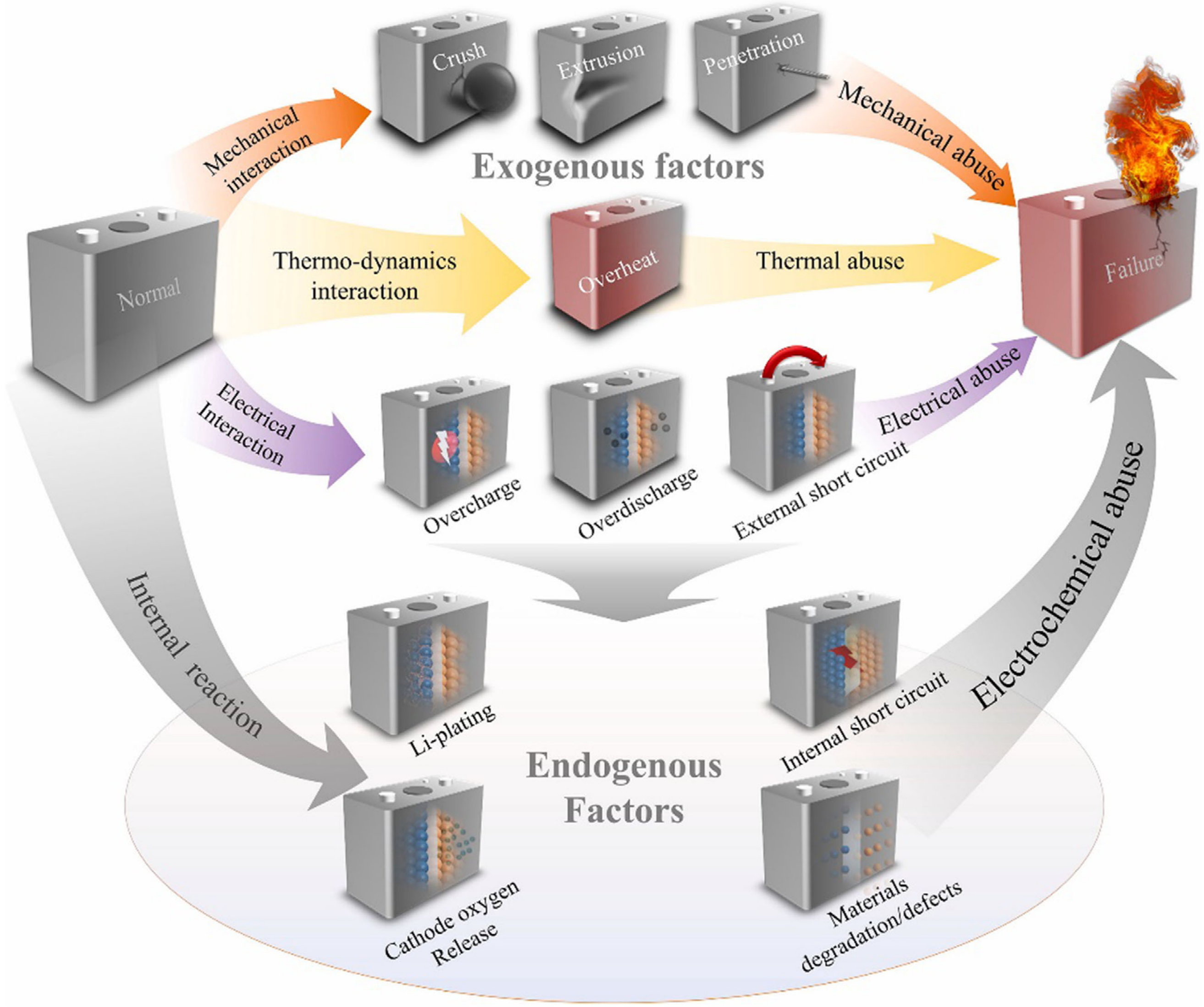

Figure 10. The process and circumstances leading to battery malfunction and failure. Adapted under terms of the CC-BY-NC-ND open access license.[109] Copyright 2024, The Authors, published by Elsevier.

3.1.1. Internal Short Circuit (ISC)

Sudden battery failures are primarily attributed to internal "soft shorts" within a cell (Figure 11b). These soft shorts create localized, non-uniform current distributions that, while initially insufficient to generate the high temperatures needed for thermal runaway, can progressively worsen. Over time, soft shorts may escalate into "hard shorts," leading to excessive current flow in specific regions, localized overheating, and ultimately, catastrophic failure.

3.1.2. Lithium Dendrites

The formation of lithium dendrites during normal battery operation can lead to separator penetration, causing severe ISC (**Figure 12**). In cases where dendrites do not fully breach the separator, soft shorts may still develop. Additionally, separators with imperfections such as pinholes, scratches, embedded particles, or uneven surfaces are more susceptible to dendrite-induced failures. Furthermore, the occurrence of soft shorts can also be attributed to inadvertent contamination, such as the presence of metallic particles on the surface of the electrode during the manufacturing process.

3.2. Battery Maintenance

3.2.1. Battery Thermal Management System

Preventing the failure of a single cell from propagating to neighboring cells is a critical concern. One effective strategy involves embedding fuses within the module to electrically isolate a compromised cell from the circuit. Furthermore, incorporating

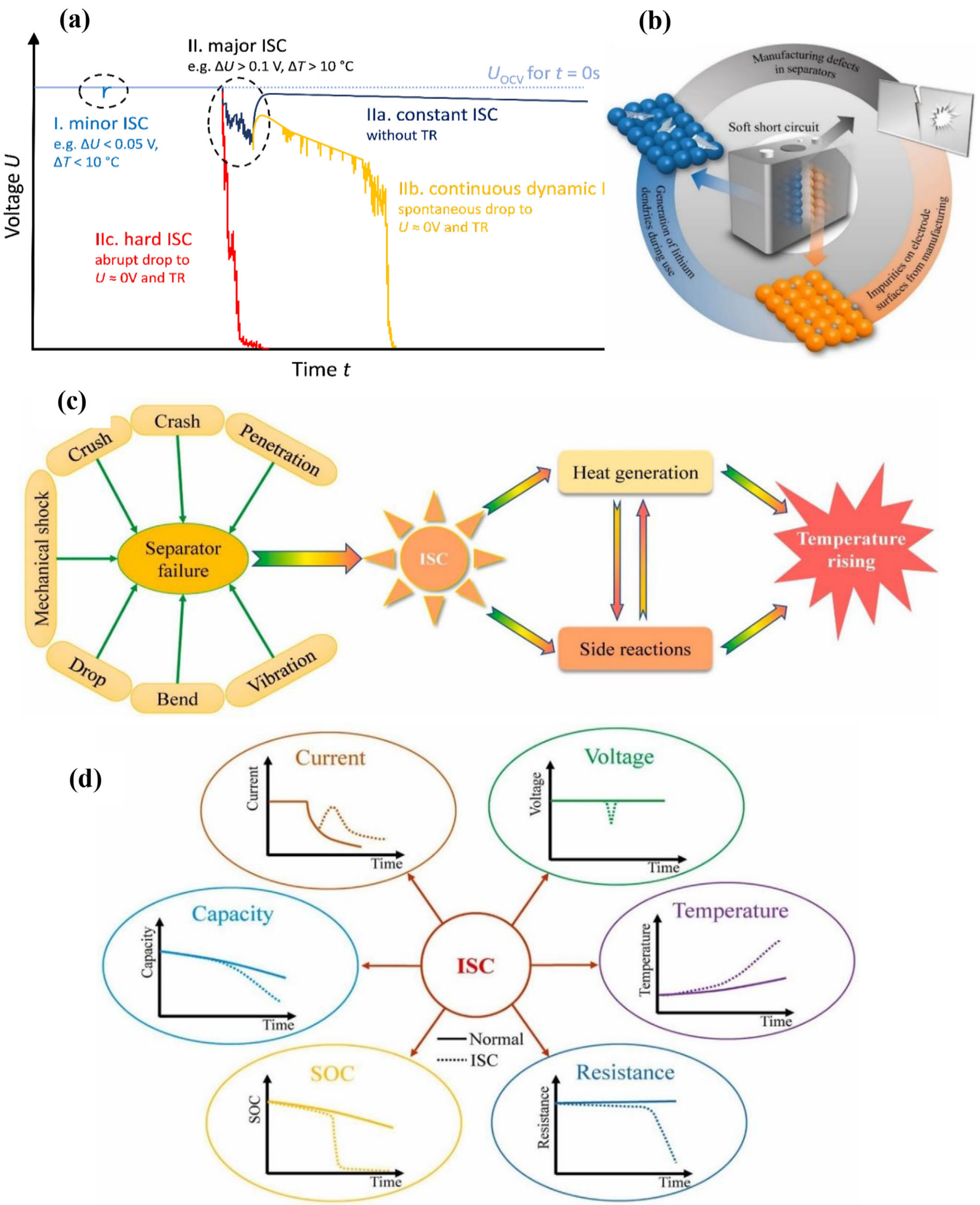

Figure 11. a) Battery different ISC types. Adapted under terms of the CC-BY open access license.[110] Copyright 2023, The Authors, published by MDPI. b) Battery soft short circuit. Adapted under terms of the CC-BY-NC-ND open access license.[109] Copyright 2024, The Authors, published by Elsevier. c) Internal Short Circuit (ISC) due to separator failure and d) ISC induces changes in the cell parameters. Adapted under terms of the CC-BY open access license.[111] Copyright 2021, The Authors, published by Elsevier.

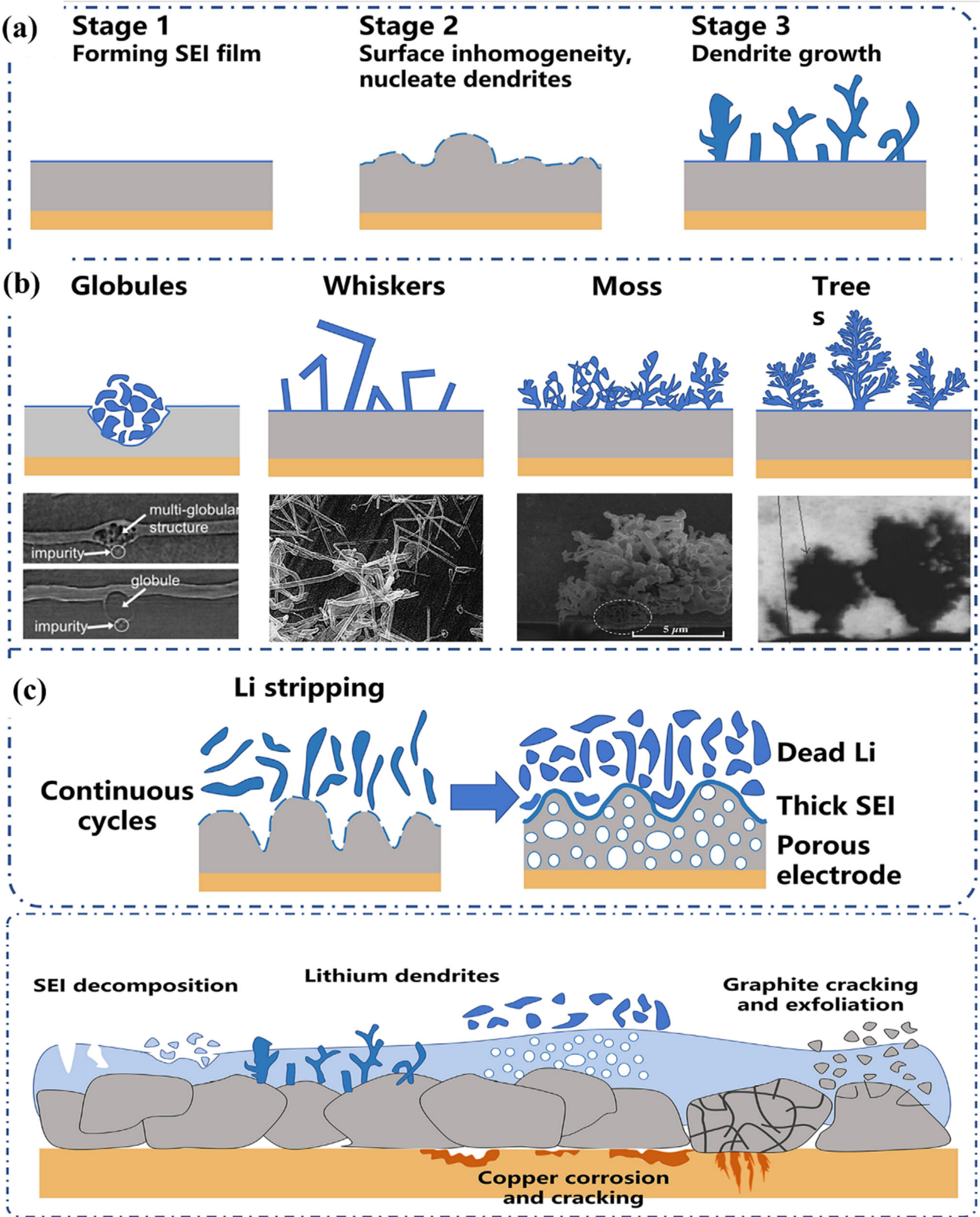

Figure 12. a) The formation and growth of lithium dendrites. b) Various morphologies of lithium dendrites. c) Phenomena associated with Li dendrites after repeated cycles. Adapted under terms of the CC-BY open access license.[112] Copyright 2023, The Authors, published by John Wiley and Sons.

flame-resistant barriers between cells and modules can significantly reduce the likelihood of thermal runaway. In severe scenarios, optimizing the battery thermal management system (BTMS) for enhanced cooling capacity can effectively dissipate heat generated during cell failure, minimizing the risk of widespread damage. The primary function of the BTMS is to regulate temperature levels and ensure uniform temperature distribution, both of which are essential for extending the lifespan and performance of LIBs. The BTMS utilizes a range of techniques, such as monitoring the State of Charge (SOC) and State of Health (SOH), to evaluate battery conditions and deliver performance metrics to electric vehicle (EV) users. By keeping the battery within its ideal temperature range, the BTMS enhances safety and operational efficiency.[113] This section examines recent research on the integration of Battery BTMS within EV platforms, offering a synthesis of key findings and advancements from prior studies. These papers[114–116] provide a comprehensive summary of critical insights, emphasizing significant progress in BTM technologies while identifying persistent challenges. For instance, enhanced cooling in a battery thermal management system (BTMS) is effective at delaying the progression of thermal runaway by reducing heat accumulation during early-stage failures, such as localized overheating or initial exothermic reactions. However, it cannot fully prevent thermal runaway once critical thresholds in temperature or material decomposition are reached. This limitation arises because thermal runaway involves self-sustaining chemical reactions (e.g., electrolyte combustion, cathode decomposition) that generate heat faster than even advanced cooling systems can dissipate. To achieve complete prevention, BTMS cooling must be integrated with material stabilization, fault detection algorithms, or physical safety mechanisms (e.g., current interrupt devices). These challenges include the reliance on idealized experimental conditions, the need for extensive real-world testing and validation, the importance of holistic economic and environmental impact assessments, and the necessity of addressing existing knowledge gaps. Overcoming these limitations including the interplay between cooling and multi-layered safety strategies is imperative to fully realize the potential of EV systems, ensuring optimal performance, enhanced safety, and long-term sustainability.

3.2.2. Battery Management System

Fault detection and diagnostics are key components of advanced control schemes, as they enable the identification and mitigation of possible difficulties in battery systems. The algorithms detect irregularities, damaged components, or potential safety issues by monitoring factors like voltage, current, temperature, and internal resistance. The utilization of fault detection and diagnostics enhances the dependability of systems, mitigates the occurrence of disastrous failures, and facilitates prompt maintenance or remedial measures. Sophisticated algorithms, real-time data collecting, and processing skills are necessary for the implementation of these advanced control systems. Battery management systems (BMS) (**Figure 13**) or smart charging systems commonly incorporate these technologies to enhance battery performance, prolong battery lifespan, and guarantee secure and effective charging processes.[117]

3.3. Data-Driven and Machine Learning Approaches for Prediction

A study represents an essential first step in predicting battery safety for EVs. Machine learning, especially when applied within multi-fidelity frameworks, is highly effective in handling complex predictive tasks. Through data-driven modeling, it becomes possible to significantly advance battery safety by developing early warning systems that can detect potential risks before they escalate. Furthermore, machine learning techniques can be utilized to create robust fault detection mechanisms, allowing for prompt identification and intervention in cases of abnormal battery behavior. This approach not only improves risk assessment but also enables proactive management, ensuring greater reliability and safety in EV batteries, thus contributing to the overall stability and performance of electric vehicles (**Figure 14**).[119]

3.3.1. Data-Driven Prediction of Battery Failure for EVs

This research explores an innovative closed-loop approach designed to reliably and accurately predict battery failure. The proposed solution utilizes advancements in cloud computing and IoT technologies. A highly integrated machine learning model, characterized by rapid adaptation and strong predictive capabilities, serves as a key element of the closed-loop system to efficiently manage and address uncertainties in models and predictions. The cloud-based framework, which utilizes data-driven models, can effectively acquire knowledge from previous automotive battery data and produce longitudinal electronic health records in the digital realm. This enables the framework to establish a continuous learning process for the prediction task, as seen in **Figure 15**. Furthermore, the utilization of a cloud-based framework in automotive applications serves as an effective means to enhance comprehension regarding battery failure. Additionally, it expedites the integration of artificial intelligence and machine learning methodologies into cloud-based BMS, commonly referred to as Cyber-BMS.[101]

Cloud-based cyber-physical systems and platform technologies have the potential to be considered a recommended approach for developing self-integrated AI models that possess the necessary capabilities and adaptability to effectively address various challenges. **Figure 16** demonstrates the utilization of a cloud-based digital solution to streamline the process of generating dates and accomplishing forecasts based on data-driven machine learning.

3.3.2. Machine Learning Techniques to Improve the Data-Driven Prediction

Prediction tasks are highly compatible with machine learning (ML), which has consequently become a prominent theoretical and practical approach in the development of self-controlled machines capable of autonomously identifying and categorizing patterns derived from training data.[122] The ML technique consists of three distinct models-dispute-based semi-supervised learning, high-dimensional unsupervised learning, and physics-guided supervised learning the technique is effectively integrated.

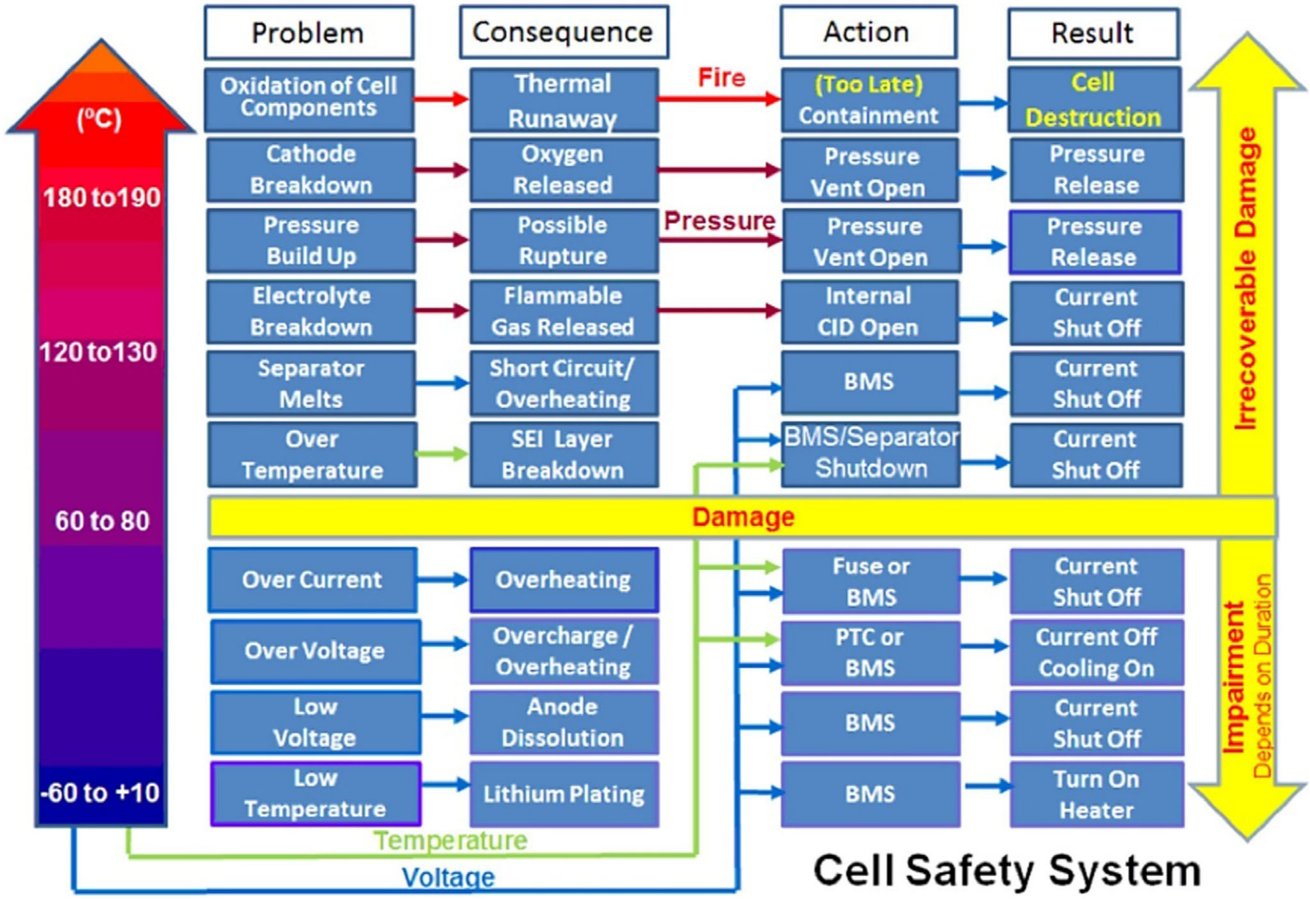

Figure 13. Battery Management System. Adapted under terms of the CC-BY open access license.[118] Copyright 2021, The Authors, published by John Wiley and Sons.

In general, the sample data can be definitively classified as positive samples (indicating failure) or negative samples (indicating safety) following a comprehensive laboratory evaluation. However, it is not only unfeasible but also unattainable to examine every car in a laboratory under meticulously regulated circumstances. To attain this objective, the prediction model exhibits a satisfactory degree of accuracy. Therefore, a closed-loop framework based on cloud technology is implemented to accomplish the specified objectives by utilizing data-driven models based on machine learning. The training data are utilized for physics-guided supervised learning modeling and assessing the efficacy of electrochemical performances. In a high-dimensional space, an unsupervised learning model is trained to effectively distinguish between many categories and accurately classify samples into either a safety or a failure group. A semi-supervised learning model is created to address the issue of ambiguous and insufficient input-output pairs. The diagram depicts the framework of the machine learning modeling process shown in **Figure 17**.

3.4. Strategies for Enhancing LIB Safety

The safety of a battery is governed by the composition of its active material and electrolyte chemistry, as well as the rate at which heat is generated and dissipated, and the ability of the battery to withstand external forces. First and foremost, the safety analysis should commence by assessing the electrode active materials, electrolytes, and separators,[123,124] as these elements are the most manageable variables. Recent advancements highlight the role of reductive gas manipulation at early self-heating stages to delay or mitigate thermal runaway. For example, Wang et al. (2022)[125] demonstrated that scavenging reactive gas intermediates (e.g., H_2, CO) during initial exothermic reactions can disrupt cascading failure pathways, providing a critical window for intervention. Similarly, innovations in solid-state electrolytes and flame-retardant additives (e.g., organophosphates, ionic liquids) have shown promise in suppressing electrolyte decomposition and reducing flammability. However, it is necessary to design techniques to mitigate the effects of thermal and electrical abuse in LIBs. Additionally, newly-produced LIBs can undergo safety testing before their integration into devices. Given that the primary reasons for safety accidents in LIBs are the production of unwanted and unmanageable heat and gas through parasitic reactions, it is crucial to concentrate on enhancing battery safety (**Figure 18**) by implementing measures to prevent excessive heat generation, maintaining the batteries within an appropriate voltage range, and enhancing their cooling capabilities.[126–130]

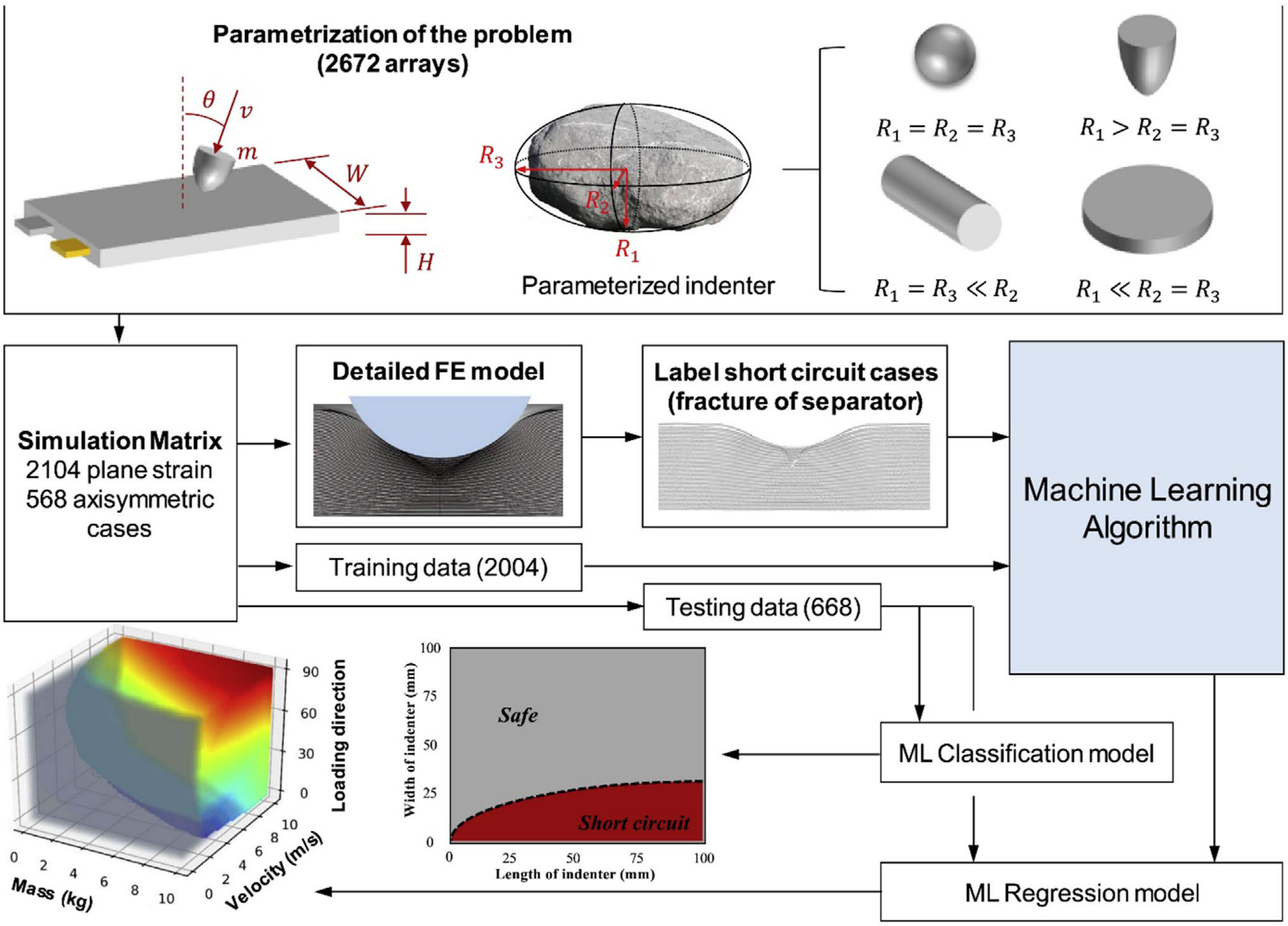

Figure 14. Flowchart illustrating the Data-Driven Safety Envelope utilizing a Machine Learning (ML) Algorithm. Adapted under terms of the CC-BY open access license.[119] Copyright 2019, The Authors, published by Elsevier.

At the cell level, strategies such as smart separators with thermal shutdown functionality and doped electrode materials (e.g., Al-doped $LiCoO_2$, Si-C composites) improve mechanical and thermal resilience. For instance, Tesla's 4680 cells employ ceramic-coated separators to enhance puncture resistance and delay internal short circuits during mechanical abuse. System-level innovations include AI-driven thermal management systems that predict thermal gradients using real-time sensor data, enabling preemptive cooling or load reduction. Recent work also emphasizes gas venting systems with selective membranes to filter flammable species (e.g., C_2H_4, HF), as uncontrolled venting exacerbates fire risks.

Mitigation strategies for ensuring the safety of energy storage systems using LIBs can be implemented at multiple levels, including material selection, individual cells, and the overall system. A holistic approach leveraging chemical, mechanical, electrical, and thermal techniques is essential to prevent failure and enhance safety. These strategies are further supported by industry practices, with specialized companies offering advanced equipment to validate and implement safety measures (see **Table 4** for key strategies, implementation examples, and industry providers). First, it is critical to reduce the probability of dangerous conditions occurring. This can be achieved through careful material selection (e.g., thermally stable electrolytes), rigorous quality control during manufacturing, and robust design principles. For instance, companies like AES SYSTEM provide environmental chambers to test material stability under extreme conditions, ensuring compatibility with safety goals. Similarly, Maccor offers cell-level testing systems to validate electrode uniformity and durability. Emerging tools, such as operando gas analyzers and high-speed X-ray imaging, enable real-time monitoring of gas evolution and structural deformation during abuse testing, bridging the gap between lab-scale research and industrial validation. In scenarios where hazardous conditions arise, immediate measures such as circuit breakers or thermal management controls can neutralize threats.[132–140] Advanced monitoring systems, such as those developed by National Instruments, enable early detection of anomalies like voltage fluctuations or temperature spikes. For example, BMW's latest BMS integrates embedded fiber-optic sensors to detect localized hot spots and gas pressure buildup, triggering failsafe protocols before thermal runaway initiates. Meanwhile, containment strategies validated through fire-resistant barrier testing by UL Solutions are critical for limiting damage during thermal runaway. By aligning these strategies with industry-proven tools and technologies (summarized in Table 4), LIB safety can be systematically

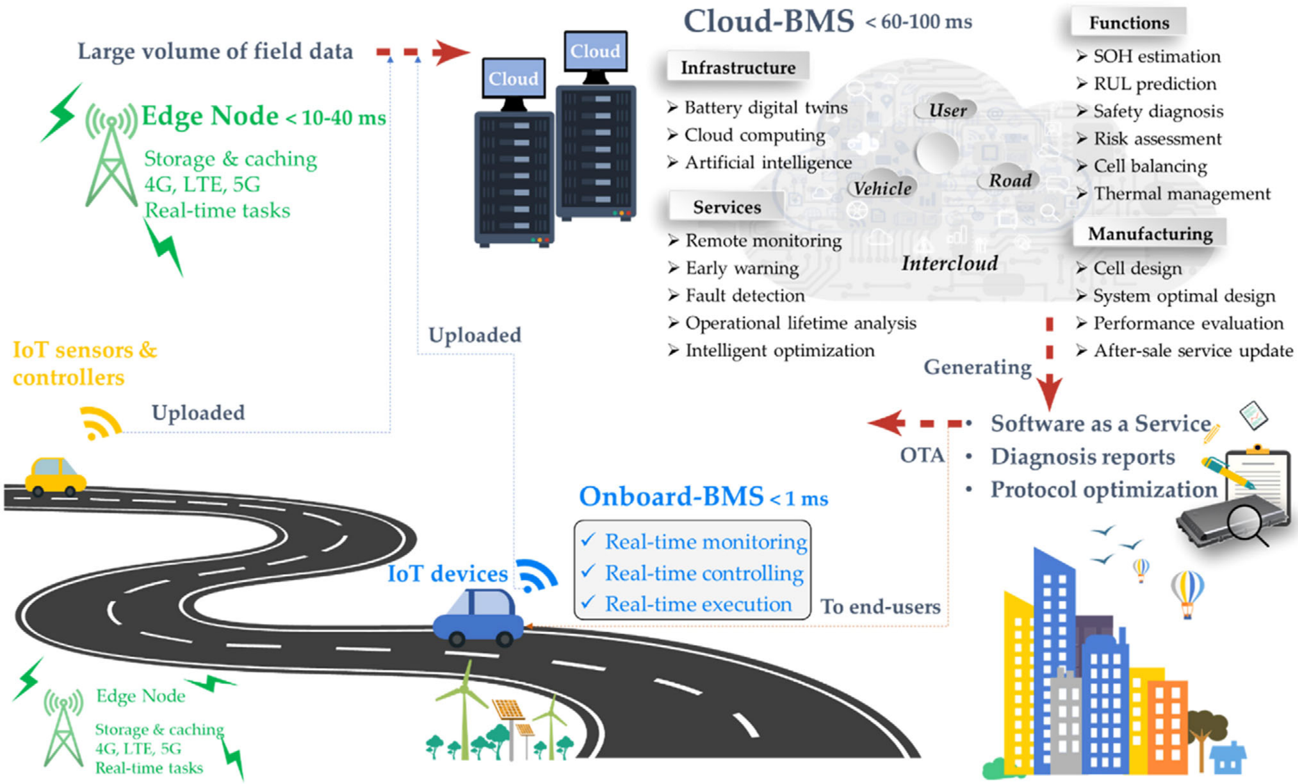

Figure 15. EV cyber-BMS schematic. Adapted under terms of the CC-BY open access license.[120] Copyright 2022, The Authors, published by MDPI.

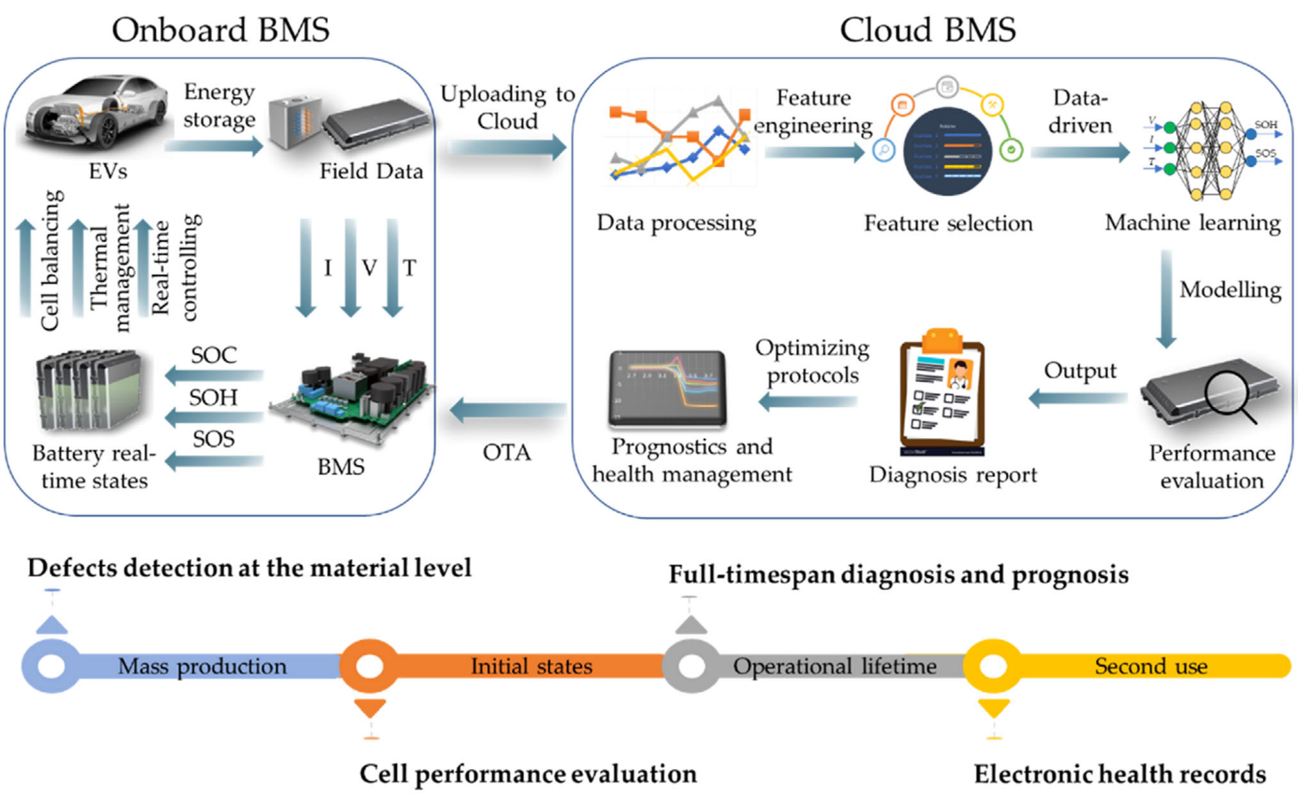

Figure 16. Diagrammatic representation of the closed loop method for cloud-based data generation. Adapted under terms of the CC-BY open access license.[121] Copyright 2024, The Authors, published by Elsevier.

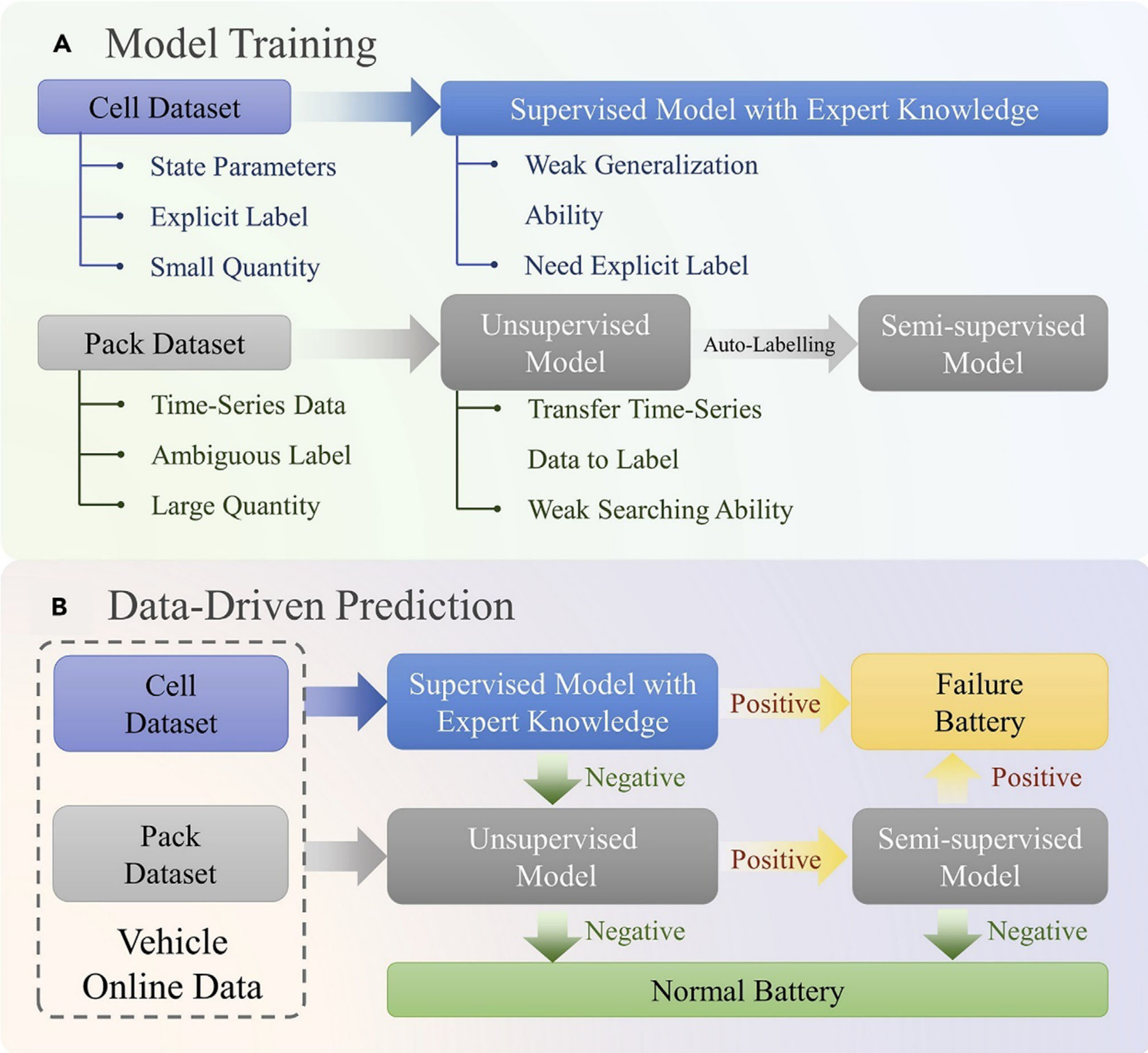

Figure 17. Data-driven prediction of battery failure for EV. Adapted under terms of the CC-BY-NC-ND open access license.[122] Copyright 2022, The Authors, published by Elsevier.

addressed across material, cell, and system levels, ensuring reliability in real-world applications.

A case study on Tesla's 4680 cells demonstrates how hierarchical safety strategies interact synergistically. Concurrently, the battery management system (BMS) employs real-time monitoring of voltage hysteresis and temperature gradients to detect early signs of stress. For example, when the BMS identifies anomalous strain in the anode (via impedance tracking), it dynamically reduces charging rates or initiates active cooling, leveraging the silicon anode's inherent thermal resilience to delay thermal runaway initiation. This integration of material design and adaptive system control creates a feedback loop where material properties enable safer operating windows, while the BMS exploits these windows to implement preventive measures. Such synergy highlights how multi-level strategies amplify safety beyond isolated improvements.[147]

4. Summary and Outlook

Batteries play a crucial role in the electrification of transportation and energy storage but face significant safety challenges, primarily due to thermal runaway a chain reaction triggered by chemical, mechanical, electrical, or thermal stress. This review systematically examines battery operational principles, using lithium-ion batteries (LIBs) as a representative example, and highlights their inherent vulnerabilities. Table 1 compares LIBs with alternative battery technologies, emphasizing the trade-offs between safety and performance. The root causes of safety failures

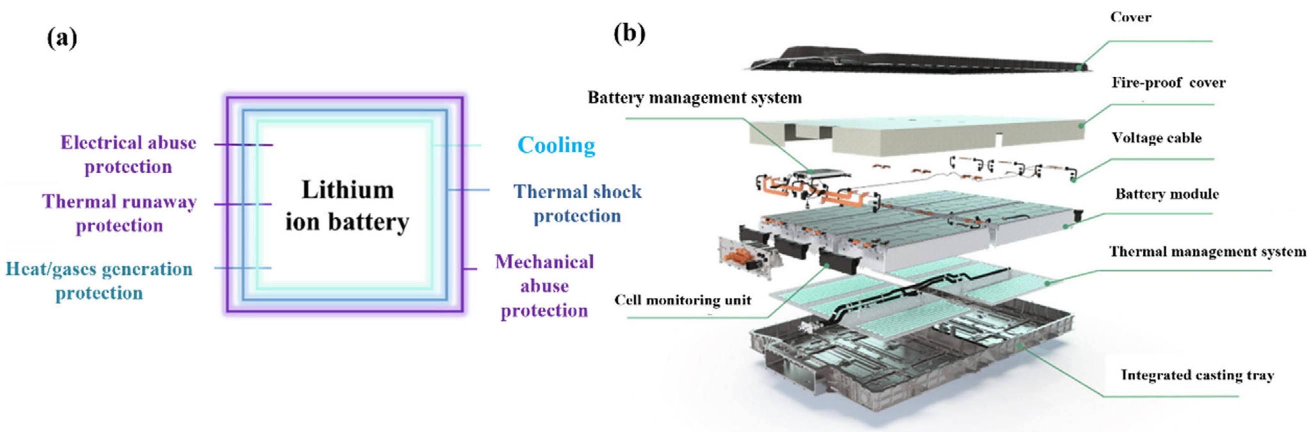

Figure 18. a) Methods for enhancing LIB safety in EVs. b) Diagram illustrating the structure of a sophisticated battery pack. Adapted under terms of the CC-BY-NC-ND open access license.[131] Copyright 2020, The Authors, published by Elsevier.

are meticulously categorized into four abuse scenarios: undesirable chemical reactions (e.g., electrolyte decomposition, cathode oxygen release), mechanical damage (e.g., crushing, puncturing), electrical stressors (e.g., overcharging, dendrite growth), and thermal instabilities (e.g., external heat, poor thermal management). These abuses collectively trigger thermal runaway, a self-sustaining exothermic process that propagates from cell to pack, often leading to catastrophic outcomes. To mitigate these risks, the paper explores advanced characterization techniques, such as in-situ microscopy and calorimetry, to diagnose failure modes, alongside maintenance strategies like BTMS for heat dissipation and BMS for real-time voltage/temperature regulation. Emerging data-driven approaches, including ML models trained on sensor data, are highlighted for their ability to predict failures (e.g., lithium plating, thermal runaway onset) and enable proactive interventions. Multi-layered safety strategies: spanning flame-retardant electrolytes, robust cell designs, and fail-safe protocols are proposed to address battery vulnerabilities holistically. Looking ahead, the review identifies transformative opportunities, such as solid-state electrolytes to eliminate flammable components, AI-driven digital twins for real-time health monitoring, and global standardization of safety testing protocols. It further emphasizes the urgent need for improved emergency response frameworks to manage EV fires, ensuring safer integration of batteries into sustainable energy systems. By bridging fundamental research with industrial applications, this work provides a roadmap for advancing battery safety without compromising performance, ultimately supporting the transition to reliable, high-capacity energy storage solutions.

4.1. Other Motivations, Challenges, and Strategies to Improve EV Batteries

Lithium-Metal Batteries: With their high energy density, lithium-metal batteries present a compelling alternative to LIBs. However, their commercialization is hindered by dendrite formation, which increases the risk of internal short circuits and potential thermal runaway. Ongoing research focuses on developing electrolyte additives, advanced separators, and protective coatings to suppress dendrite growth and improve safety.

Solid-State Batteries: Solid-state batteries (SSBs) offer transformative safety advantages by replacing flammable liquid electrolytes with non-flammable solid materials (e.g., ceramics, polymers), effectively mitigating risks of thermal runaway, dendrite-induced short circuits, and electrolyte leakage. However, ceramic electrolytes, despite their stability, face challenges due to mechanical brittleness, which can lead to interfacial cracking and delamination during cycling. To address these limitations, industry leaders are pioneering material innovations and scalable manufacturing strategies. For instance, QuantumScape employs a flexible ceramic electrolyte and anode-free design to enhance mechanical resilience, targeting commercial EV integration post-2025. Toyota, in collaboration with Panasonic, utilizes sulfide-polymer composite electrolytes and multilayer lamination techniques to reduce stress in hybrid prototypes, aiming for limited fleet deployment by 2027–2028. Similarly, Solid Power leverages sulfide-based electrolytes and roll-to-roll production to minimize interfacial strain, with EV testing planned for 2025. ProLogium's oxide-ceramic/polymer composites and self-healing architectures further exemplify progress in fault-tolerant designs, supported by partnerships with automakers like NIO. Industry timelines project pre-commercial cell delivery and prototype validation by 2024–2025, followed by gradual scaling of production methods (e.g., hybrid electrolytes, advanced sintering) to achieve cost competitiveness and energy density parity with lithium-ion batteries by the early 2030s. These advancements underscore a clear pathway toward SSB adoption, driven by material hybridization, mechanical durability enhancements, and rigorous industrial validation.

Material Innovations: Advancements in battery materials are crucial for enhancing safety. Researchers are exploring new electrolyte formulations, high-temperature-resistant cathode materials, and dendrite-resistant anodes to improve thermal stability, mechanical integrity, and overall battery reliability.

Detection, Monitoring, and Fault Prediction: i) Advanced sensors and monitoring systems can detect temperature spikes, gas emissions, and other indicators of potential fires. Early detection can trigger automatic fire suppression systems or alert re-

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Table 4. Mitigation Strategies for LIB Safety in Energy Storage Systems.

Strategy	Objective	Implementation	Example Companies/Equipment
Material Selection	Reduce inherent risks through stable materials.	Use thermally stable electrolytes, fire-retardant separators, and robust electrodes.	AES SYSTEM: Thermal Chambers for material stability testing.[141]
Cell-Level Safety	Minimize failure risks in individual cells.	Quality control during manufacturing (e.g., electrode coating uniformity checks).	Maccor: Battery Cycler Test Systems for cell durability and abuse testing.[142]
System-Level Safety	Prevent cascading failures in the battery pack.	Robust electrical/thermal design, modular architecture, and isolation mechanisms.	Keysight Technologies: Battery Test Systems for system-level performance validation.[143]
Thermal Management	Enhance thermal stability under stress.	Active cooling/heating systems, phase-change materials, and heat-resistant coatings.	Thermal Hazard Technology: Calorimeters for heat generation analysis.[144]
Early Detection & Warning	Identify anomalies before catastrophic failure.	Real-time voltage/temperature monitoring, gas sensors, and AI-driven diagnostics.	National Instruments: Battery Management Test Systems for predictive analytics.[145]
Containment	Limit damage propagation during thermal runaway.	Fire-resistant barriers, venting mechanisms, and explosion-proof enclosures.	UL Solutions: Battery Fire Exposure Chambers for fire containment testing.[146]

sponders. ii) Enhanced BMS can optimize charging and discharging processes to minimize the risk of overheating and fire risks. iii) AI and ML models are being developed to predict battery faults and improve health monitoring, enabling timely intervention.

Advanced Cooling Technologies: i) The use of liquid nitrogen or other cryogenic agents can rapidly cool battery cells, preventing thermal runaway and extinguishing fires. ii) Integrating Phase Change Materials (PCMs) into battery packs can help absorb excess heat and prevent temperature spikes that lead to fires.

Automated Fire Suppression Systems: EVs could be equipped with built-in fire suppression systems that activate automatically in case of fire, using inert gases or other extinguishing agents to quickly control and suppress flames. Vehicles can also communicate with charging stations and emergency services to provide real-time data on battery status and potential fire risks. Additionally, significant advancements are needed in EV fire suppression methods, such as the development of firefighting robots, drones, fire blankets, and specialized fire suppression foams.

Training and Standardized Guidelines: Specialized training programs for firefighters can enhance their ability to respond effectively to EV fires, focusing on the unique challenges and best practices. Developing standardized protocols for EV fire response will ensure consistency and safety across different regions and emergency departments.

Recycling and End-of-Life Management: Sustainable recycling methods and second-life applications are being explored to minimize environmental impact and enhance resource utilization. For the electric vehicle market to experience sustainable growth, it is essential to address the lifecycle impacts of batteries, which includes recycling and repurposing of batteries' components. Establishing secure, efficient, and environmentally friendly end-of-life procedures for EV batteries will present both a significant challenge and a valuable opportunity.

4.2. Battery Selection and Application

Every battery type presents unique benefits and encounters particular challenges. Selecting the appropriate battery for EV use depends on considerations like cost, energy density, safety, and the specific needs of the vehicle. Lithium-ion and solid-state batteries are currently the leading choices for EVs because of their high energy density, extended cycle life, and relatively lightweight design. At the same time, continuous research efforts are focused on improving safety, performance, and cost-effectiveness across different battery technologies to address the changing demands of the industry.

4.3. Future Directions in EV Battery Safety

Predictive Maintenance and Monitoring: Advanced AI-driven algorithms for health monitoring and early fault detection are critical for ensuring battery reliability. These models need to be refined for real-world applications to enhance prediction accuracy and reduce operational risks.

Safety by Design: Next-generation batteries will prioritize intrinsic safety through innovations in materials and architecture. Solid-state batteries, which replace flammable liquid electrolytes with non-combustible solid alternatives, represent a paradigm shift in eliminating thermal runaway risks. Concurrently, self-healing materials such as polymers that autonomously repair electrode cracks or suppress dendrite growth will extend battery lifespan and reliability. Modular battery designs, featuring isolated cell compartments, will mitigate cascading failures by localizing thermal events. These advancements will be complemented by 3D-printed electrodes and nanostructured separators, which enhance ion transport while mechanically resisting dendrite penetration, ensuring safety without compromising performance.

Standardization and Regulation: Harmonizing global safety standards is critical to accelerating EV adoption. Future efforts must establish unified testing protocols for thermal runaway propagation, crash resilience, and lifecycle durability, enabling cross-border certification of battery systems. Regulatory bodies will collaborate with manufacturers to develop third-party validation frameworks, ensuring compliance with emerging benchmarks such as ISO 6469 and UNECE R100. Open-data initiatives will further drive progress, fostering transparency by sharing anonymized safety data (e.g., failure modes, aging patterns) across academia and industry. Such collaboration will streamline innovation while maintaining rigorous safety guardrails.

Circular Economy and Safety: Developing safe recycling processes and exploring second-life applications for EV batteries can significantly reduce environmental impacts. Ensuring the safety of these processes is essential for their long-term viability.

Collaboration between industry, academia, and regulatory bodies is imperative to address the multifaceted safety challenges of EV batteries. Cross-disciplinary partnerships can accelerate innovation, establish robust safety standards, and foster the development of next-generation battery technologies. By prioritizing safety, sustainability, and education, the automotive sector can ensure that EVs become a cornerstone of global transportation networks. In conclusion, while substantial progress has been achieved, the path forward offers diverse opportunities to enhance the safety, efficiency, and sustainability of EV batteries. By embracing innovation, promoting collaboration, and emphasizing safety by design, the vision of a safe, reliable, and efficient EV ecosystem can be realized.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

artificial intelligence, battery failure, battery safety, electric vehicle, machine learning, prediction, thermal runaway

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