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Review Paper

Addressing Fire Safety, Ground Impact Resistance, and Thermal Management in Composite EV Battery Enclosures: A Review

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Abstract

Lithium-ion batteries are fundamental to modern electric vehicles, offering high energy density, long cycle life, and low self-discharge rates. However, thermal runaway—a critical safety issue involving uncontrolled temperature increases—can lead to fire or explosion. Ensuring flame retardancy is crucial in accidents where battery packs are exposed to external fires. Additionally, battery packs are susceptible to mechanical stresses and potential damage from ground impacts like debris or uneven road surfaces. Effective thermal management significantly impacts capacity and longevity. This review emphasizes the importance of researching flame retardancy, ground impact resistance, and thermal management, especially in composite battery enclosures. Composites serve as a lightweight alternative to metals and help overcome one of the main constraints of EVs, which is weight. Ground impact refers to the physical force battery packs endure during collisions, hitting potholes, debris, or accidents. Therefore, understanding the effects of ground impact on battery enclosures is crucial for design considerations. Effective thermal management is also essential, as it directly affects the performance and safety of Lithium-ion battery packs in EVs.

Keywords: Flame retardancy; Ground impact resistance; Battery thermal management; Composite; Battery enclosures

1. Introduction

Lithium-ion batteries are the cornerstone of modern electric vehicles (EVs), offering a high energy density, long cycle life, and relatively low self-discharge rates compared to other battery technologies. These batteries power the drive motors of EVs, providing the necessary energy for propulsion while also supporting auxiliary functions such as lighting, climate control, and infotainment systems. The design and optimization of Lithium-ion batteries are critical to achieving the desired range, performance, and safety standards of EVs [1]. As the adoption of EVs accelerates globally, advancements in Lithium-ion battery technology are essential to overcome challenges related to energy storage capacity, charging time, thermal management, and overall durability [2]. The energy density of Lithium-ion batteries stands as their most critical parameter, with methods and technologies concerning the cathode, anode, and electrolyte being pivotal for its enhancement [3]. Concurrently, charging time represents another vital consideration, influencing public acceptance of EVs significantly. Studies have shown that charging time is the most influential factor, followed by driving range and the availability of charging infrastructure [4]–[7] Charging time involves the availability of charging stations and scheduling management, which includes arrival time, charging time, and departure time, all of which have high levels of uncertainty [8]. Electric vehicle users need approximately 2 to 14 hours to recharge their batteries [9]. This relatively long charging time influences users' attitudes, which can be categorized into several levels: cognitive, emotional, behavioral, and physiological [10]. Regarding battery thermal management, high temperatures pose risks of thermal runaway in Lithium-ion batteries [11]. The battery operation in EVs is classified into three modes: charging, standby, and driving. During charging, parameters such as cut-off voltage, current, and ambient temperature cause the battery temperature to increase; high cut-off voltage and current lead to a rise in temperature. In standby conditions, the battery temperature is influenced by the ambient temperature. While driving, factors such as driving behavior, vehicle design, and environmental temperature affect the battery temperature [12]. Furthermore, advancements in battery cell design [13] and increasing battery capacity [14] have been explored to extend battery lifespan. Battery capacity is influenced by the electrode materials, with commercially used graphite reaching its limits and prompting further research into anode materials, including carbon, metal oxides, silicon, and germanium [15]. Tesla has addressed capacity demands by transitioning from the 18650 to the 21700 format, increasing cell capacity from around 2 Ah to approximately 5 Ah. Consequently, the overall battery pack capacity requirement has risen from 20 kWh in 2010 to about 54 kWh in 2021 [16]. Despite these advancements, an energy management system remains crucial to ensure efficient energy use, even with the same battery pack capacity [17], [18]. This ongoing evolution underscores the importance of continuous research and development in battery materials, architecture, and management systems to meet the growing demands of the electric vehicle (EV) market.

Thermal runaway in Lithium-ion batteries is a critical safety issue characterized by an uncontrollable increase in temperature, often leading to fire or explosion [19]. This phenomenon occurs when the heat generated within the battery exceeds the heat dissipated to the environment, causing the internal temperature to rise rapidly [20], [21]. Several mechanisms can trigger thermal runaway, including overcharging, over-discharging, internal short circuits, and external heating. During thermal runaway, the electrolyte decomposes, generating flammable gases, while the anode and cathode materials may also break down, releasing additional heat [22]. The reaction is highly exothermic, meaning it generates a significant amount of heat, further accelerating the temperature rise and leading to a self-sustaining cycle of increasing heat and reaction rates. The primary causes of thermal runaway are closely linked to the battery's operational and environmental conditions. Overcharging is a common trigger, as it can lead to the breakdown of the electrolyte and the deposition of Lithium metal on the anode, increasing the risk of short circuits [23]. During overcharging cycles, one consequence is the decomposition of the electrolyte, which leads to increased battery impedance, premature aging, and excessive temperature rise [24]. Mechanical damage or manufacturing defects can also cause internal short circuits by allowing the electrodes to come into direct contact, bypassing the electrolyte [25]. Excessive mechanical stress can cause internal short circuits in batteries. This process involves the initiation of deformation, triggering, and evolution of the internal short circuit, which can ultimately lead to thermal runaway [26]. Additionally, high ambient temperatures or inadequate cooling systems can exacerbate the heat generation within the battery, pushing it into thermal runaway [27].

As various factors could contribute to such a phenomenon, how to prevent thermal runaway must first begin with proper identification: what are the potential sources? Are they caused by some abuses, faults, battery aging, or a combination of them? If it is purely caused by the rise in internal temperature, a properly designed Battery Thermal Management System (BTMS) should be able to prevent it. If it is caused by external heat/fire, then a layer of protection, such as fireproof materials, could be a solution. A fail-safe battery management system could prevent many incidents from occurring [28]. In general, a thermal runaway early detection system should have always been integrated into the EV battery pack. Furthermore, thermal runaway prevention strategies must not be limited to a battery system level but to the modular, cell, and even battery cell materials levels. From a temperature-sensitive coating to modifications of cathodes and anodes, various research studies have been reported and can be applied to designing a battery pack [19], [21], [29].

Research on BTMS for lithium-ion batteries mainly suggests the use of cooling media such as air, liquid, phase change materials (PCM), or a combination (hybrid system) [22]. Several literature surveys on findings regarding thermal runaway prevention strategies using air cooling media, especially if the battery cooling load is relatively low. In designing an effective BTMS, the placement of all the batteries also plays an important role. The arrangement of battery cells in an aligned configuration is better than staggered and cross configurations [30]. The placement of the air inlet at the top and the exhaust at the bottom results in higher cooling efficiency compared to other inlet and exhaust positions [31]. Vortex generators and jet inlets in a unidirectional air flow reduce the temperature deviation, improving uniformity to below 5°C [32]. The addition of air tubes around the battery results in a temperature uniformity target of 3°C [33]. On the other hand, there are also findings of thermal runaway prevention strategies based on liquid cooling media. Temperature uniformity of less than 5 °C is achieved by using a variable aluminum block with a 3 mm gradient and a linear configuration [34]. A "fork" type cold plate has been designed, requiring a flow rate of 48 mL/s to maintain a temperature uniformity below 5 °C [35]. Utilizing Tesla valves for liquid mixing enhances both cooling efficiency and temperature uniformity [36]. Findings on PCM materials have also successfully prevented thermal runaway. An optimal proportion of 7% EG in a paraffin-based composite PCM has been identified [37]. A novel PCM consisting of graphene-coated nickel (GcN) foam saturated with paraffin has been developed, offering 23 times higher thermal conductivity than pure paraffin [38]. Next, thermal runaway prevention strategies involving hybrid systems. A novel approach has been developed by integrating water evaporation with convective and conductive effects [39]. Liquid jackets were applied to each battery, and passive air cooling techniques were employed to achieve a temperature uniformity of 1.3 °C [40]. Temperature uniformity of 1 °C is attained by adjusting the liquid flow rate to 54 mL/min and the PCM thickness to 0.65 mm [41]. At ambient temperatures above 60 °C, the electrolyte material evaporates, and the electrodes decompose [42]. This becomes a challenge when the balance of temperature distribution across each battery cell in the module or pack is not achieved [43]. Understanding these mechanisms and causes is crucial for developing effective thermal management strategies and safety protocols to mitigate the risks associated with Lithium-ion battery usage in EVs and other applications.

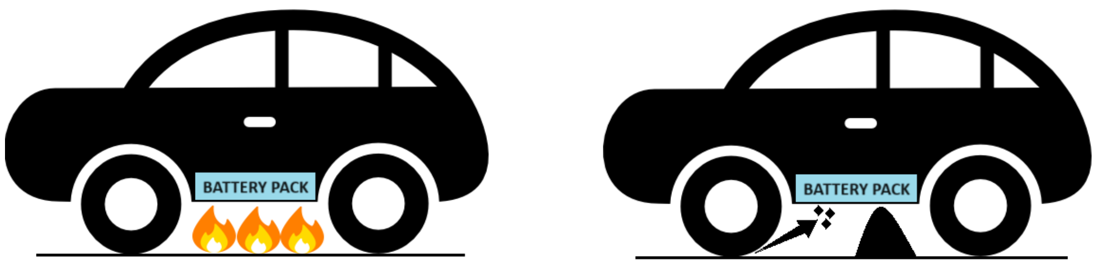
Safety standards and regulations for Lithium-ion battery packs in EVs are essential to ensure safe and reliable operation. ISO 12405-3 specifies the test procedures for Lithium-ion battery packs and systems intended for use in electric and hybrid EVs, focusing on performance, reliability, and safety requirements [44]. UN/ECE R100.02, a regulation from the United Nations Economic Commission for Europe, addresses the safety requirements concerning the electric powertrain of road vehicles, including specific provisions for Lithium-ion batteries, such as protection against overcharging, thermal runaway, and mechanical impacts [45]. Additionally, IEC 62660-2 outlines the safety requirements and tests for rechargeable Lithium-ion cells and batteries for industrial applications, including EVs [46]. These standards collectively ensure that Lithium-ion battery packs in EVs meet stringent safety criteria, covering aspects such as electrical performance, mechanical integrity, and thermal management to protect against potential hazards during normal operation and in the event of accidents or misuse. Using the UN/ECE R100.02 procedure, fire exposure tests on batteries indicate that thermal runaway is more likely to occur after fire exposure as the temperatures inside and around the battery start to equalize [47]. The behavior of thermal runaway during battery combustion includes battery expansion, jet flame, and stable combustion [48]. The jet flame is particularly hazardous as it can ignite flammable materials. The risk of fire in Lithium-ion battery packs increases significantly, especially when vehicles are parked near buildings. The danger extends not only to the vehicle itself but also to nearby structures. Electric vehicles with battery capacities of 15-25 kWh present a similar fire risk to conventional vehicles [49]. Fires caused by battery failures can lead to prolonged exposure to high temperatures, potentially inducing excessive deformation in load-bearing steel elements [50].

When temperatures exceed 300 °C, steel structures begin to lose their ability to support static loads effectively [51]. Beyond structural deformation, intensified fires can compromise human safety and hinder evacuation efforts [52].

In an accident scenario where the battery pack is exposed to fire from outside the vehicle, ensuring the battery pack's flame retardancy is crucial for safety. Such scenarios might involve situations where the vehicle catches fire due to a collision with a fuel-carrying vehicle or an external fire source [53]. **Figure 1a** illustrates this situation by showing the fire exposure of an EV with a battery pack located beneath the floor. In these cases, the battery pack must be able to withstand external flames and high temperatures without leading to a thermal runaway or explosion. If such conditions occur, the internal battery pack temperature should not exceed 120 °C, and it would be even better if the temperature remains below 80 °C [54].

Ground impact poses a significant risk to EV battery packs, as it can lead to both immediate and long-term safety issues [55]. When a vehicle experiences a ground impact, such as from debris or uneven road surfaces, the battery pack is subjected to mechanical stresses and potential damage. This can result in physical deformation, cracking, or puncturing of the battery enclosure, compromising its structural integrity [56]. The immediate effects of such damage can include short circuits within the battery cells, which may lead to thermal runaway, fires, or even explosions [57]. Over time, the compromised battery pack may also suffer from reduced efficiency, capacity loss, and increased risk of failure. **Figure 1b** illustrates the risk of ground impact due to a speed bump and the scattering of debris. Finite element simulation results indicate that the bottom protective plate with a blast-resistant adaptive sandwich structure effectively reduces the deformation of battery cells [58]. Equally important is that battery thermal management is crucial in EVs due to its direct impact on battery capacity and longevity. Lithium-ion batteries, commonly used in EVs, operate optimally within a specific temperature range. Elevated temperatures can accelerate chemical reactions within the battery cells, leading to degradation of the electrolyte and electrode materials, thus reducing overall battery capacity and cycle life [59]. On the other hand, excessively low temperatures can increase the internal resistance of the battery, limiting its power output and efficiency [60]. Therefore, effective thermal management systems are designed to regulate battery temperature, ensuring it remains within the ideal operating range. The study that varied several anode materials recommended an optimal operating temperature for Lithium-ion batteries between 20-50 °C [61].

Furthermore, research into flame retardancy, ground impact resistance, and thermal management of battery packs is crucial, particularly concerning composite battery enclosures. Composite materials offer advantages like weight reduction and design flexibility, making them increasingly popular in EV applications [62], [63], including the potential to form structural battery power composite [64]. However, ensuring these materials meet stringent safety standards for flame retardancy, impact resistance, and effective thermal management remains a challenge. Glass Fiber Reinforced Polymer (GFRP) is a composite material commonly used for vehicle components, but it is easily flammable and requires the addition of flame retardants to enhance its flame retardancy [65].



(a) (b)

Figure 1. (a) Thermal load scenario of a battery pack from a fire outside the vehicle, and (b) Ground impact scenario on the battery pack

Additionally, GFRP components are difficult to machine because they are harder and more brittle than steel or aluminum [66]. Comprehensive studies are needed to develop composite structures that can effectively mitigate fire risks, withstand impacts, and efficiently dissipate heat to ensure the safety and longevity of EV battery systems. These efforts will contribute significantly to advancing the reliability and safety of composite battery enclosures in EVs. Although flame retardancy, ground impact resistance, and thermal management have been individually studied for lithium-ion battery systems, there is a notable gap in the existing literature regarding their integration altogether, especially when considering composite materials for battery enclosures. Current studies often focus on isolated features, leaving a lack of understanding of how these aspects can be optimized together to meet the demands of modern electric vehicles. This review aims to address this gap by collaborating on recent advancements across these domains and providing insights into holistic design strategies for safer and more efficient battery systems.

The aim of this review paper is to provide insight into recent studies on EV Lithium-ion battery packs. This includes a comprehensive examination of flame retardancy, impact resistance, and thermal management, especially in composite material applications. By evaluating current research findings, the paper aims to highlight the state-of-the-art developments and identify potential areas for future investigation. The ultimate goal is to contribute to the enhancement of battery safety, performance, and reliability in EVs. This review is divided into several sub-sections: studies related to flame retardancy of composite materials, the ground impact resistance of composite battery enclosures, and Lithium-ion battery thermal management. All three factors are considered crucial in ensuring the safety of Lithium-ion battery applications for EVs. The flame retardancy of composite materials, the ground impact resistance of composite battery enclosures, and the thermal management of lithium-ion batteries are subjectively considered critical factors in the design of electric vehicle battery packs. While these priorities may differ from other bibliographic findings, they offer a robust foundation for initial studies and the design of composite-based lithium-ion battery enclosures. This review excludes factors such as vibration and shock safety, as well as electrical safety. This paper focuses on studies published between 2014 and 2024, emphasizing the recent advancements and trends in the development of flame retardancy, ground impact resistance, and thermal management for lithium-ion battery packs.

2. Flame Retardancy of Composite Materials

In terms of material properties, composites generally have lower thermal conductivity compared to metals. This characteristic is advantageous because heat from an external fire is not efficiently transferred to the battery. **Figure 2** illustrates a comparison between metal and composite battery enclosures. In **Figure 2**a, the metal enclosure conducts heat from the fire directly to the battery, potentially putting it at risk due to excessive heat exposure. In contrast, **Figure 2**b shows a composite enclosure acting as a thermal insulator, allowing a significantly lower heat transfer to the battery. However, prolonged exposure to fire can still ignite the composite material. To mitigate this risk, flame retardant additives are incorporated to delay combustion further. In **Figure 2**b, the flame retardant creates a fire barrier, preventing the flames from reaching flammable components [67].

The flame retardancy of composite materials for Lithium-ion battery enclosures is a critical aspect of ensuring the safety and reliability of EVs. One of the primary challenges in enhancing flame retardancy is balancing the material's mechanical properties with its ability to resist ignition and prevent flame propagation. Traditional materials often compromise structural integrity when treated with flame retardants, necessitating advanced solutions. Traditional flame retardants typically experience issues with dispersion and migration [68]. Traditional flame retardants, such as brominated flame retardants, contaminate water, dust, air, and soil, negatively impacting human health [69]. Similarly, chlorinated organophosphate flame retardants are carcinogenic [70]. Recent technological advancements have focused on integrating flame retardant additives such as aluminium tri-hydroxide (ATH), magnesium hydroxide (MH),

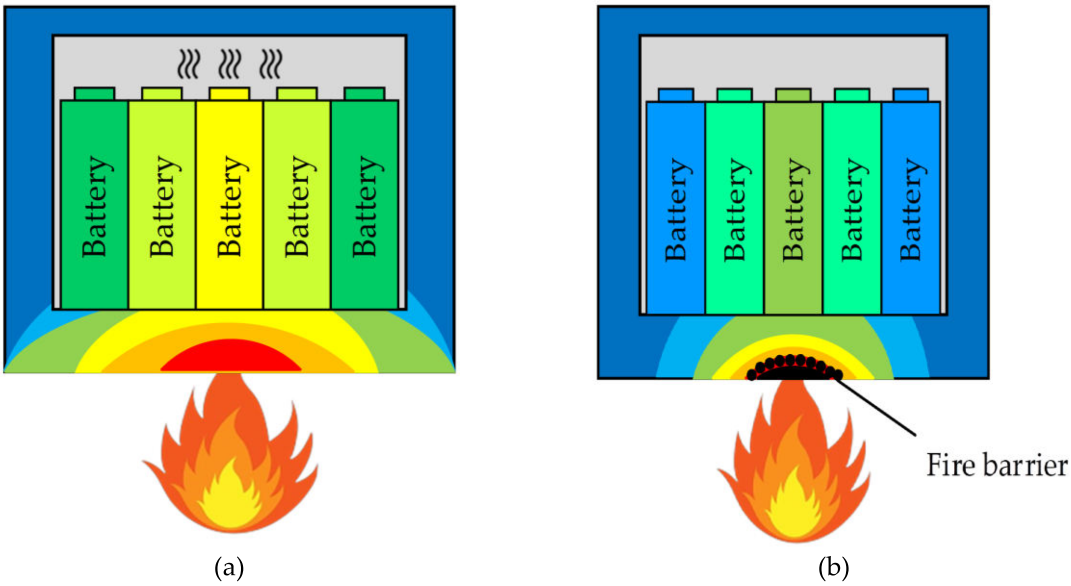


Figure 2. Illustration of battery enclosure material: (a) metal, and (b) flame retardant composite

and ammonium polyphosphate (APP) into composite matrices. Studies have shown that these additives can significantly improve the flame retardancy of composites without severely impacting their mechanical properties. Even among these flame retardants, hybridization can be performed to achieve an optimal balance between flame retardancy and mechanical properties. The combination of ATH and APP can result in a reduction in the mass loss rate in unsaturated polyester (UP) composites [71]. These findings, based on thermogravimetric analysis results, demonstrate that using two flame retardants together can enhance the flame retardancy of composites. Additionally, to mitigate the adverse effects on mechanical properties, ATH can be substituted with pristine montmorillonite (MMT) [67]. Consequently, the combination of ATH and MMT in composites achieves an optimal balance between flame retardancy and mechanical properties.

Polypropylene combined with 20% ATH and 5% boric acid (BA) demonstrates significantly higher flame retardancy compared to neat samples and those with ATH alone [72]. Innovations such as microencapsulation have also been explored to enhance the dispersion and efficacy of flame retardants in the composite matrix. The microencapsulation of APP in UP-based composite systems successfully improved flame retardancy, as indicated by meeting the UL94 V-0 standard [73]. A study on the hybridization of ATH and APP, enhanced through innovative microencapsulation techniques, shows improved flame retardancy compared to plain APP [74]. Additionally, researchers are investigating the use of intumescent coatings and nanocomposites to further improve flame retardancy while maintaining lightweight and strong structural characteristics. A material comprising UP, APP, pentaerythritol, and melamine can delay the ignition process even when used as a coating on a substrate [75]. Coating with a combination of melamine polyphosphate and graphite in a film-forming agent acrylic resin enhances flame retardancy, heat resistance, and electromagnetic interference shielding [76]. In nanocomposite materials, the quantity and size of nanoparticles offer opportunities to achieve a balance between flame retardancy and mechanical properties [77]. Single-walled carbon nanotubes demonstrate superior flame retardancy compared to conventional flame retardants due to the increased surface area interaction between the polymer and the nanofillers [78].

These advancements are crucial in meeting stringent safety regulations and ensuring the widespread adoption of EVs. Table 1 summarizes the approaches and methods employed in studies aimed at enhancing the flame retardancy of composite materials. The discussion of the advantages and disadvantages of each method and innovation provides an overview of their implementation in Lithium-ion battery enclosure designs. On the other hand, an interesting aspect worth adding to this discussion is the long-term durability of composite materials after the incorporation of flame retardants. Plant-based fiber composite has an advantage as a more environmentally friendly composite, but it is typically unstable temperature-wise, leading to weak durability [79]. Flame retardant composites can last for decades indoors but may have a significantly shorter lifespan in outdoor environments [80]. De et al. [81] have specifically discussed the recycling issues of polymer composites. The recycling advantages require a substantial amount of recyclable resin in its manufacturing processes [82]. The key indicators of composite aging and degradation include interfacial debonding, matrix microcracking, interfacial sliding, fiber breakage, fiber microbuckling, particle cleavage, and void growth [83]. These phenomena can compromise the structural integrity and performance of composites over time. A solution to slow down composite aging and degradation is the addition of antioxidants [84]. Additionally, the development of flame retardant composites can be further enhanced by considering recyclability through mechanisms such as exchangeable crosslinks [85]. This approach would allow for improved sustainability by enabling easier recycling and reducing environmental impact.

Table 1 demonstrates that composite employing multiple outperform single flame retardant systems, particularly in achieving a balance between flame retardancy and mechanical properties. However, this may lead to a more complex and expensive manufacturing process. The test results show no significant change in tensile strength in composites with multiple flame retardants, indicating only minor variations, whether an increase or decrease, which are considered acceptable. Moreover, methods such as microencapsulation and nanoparticles show enhanced flame retardancy compared to conventional commercial flame retardants. Furthermore, flame retardant composites have a long lifespan when used indoors, but exposure to outdoor conditions can significantly shorten their durability. Key aging indicators, such as fiber breakage and matrix microcracking, can undermine the material's structural integrity, though antioxidants can help slow down this degradation process. Improving recyclability will help reduce the environmental impact caused by the increased use of flame retardant composites. Reviews on flame retardants and their improvements can offer valuable insights for designing composite materials for Lithium-ion battery enclosures.

Table 1. Common flame retardants and their side effects

Methods or innovations	Flame retardancy	Mechanical properties	Additional information	Ref.
Single flame retardant: Variations in ATH composition	Flame retardancy increases with a rise in ATH concentration	At the highest ATH concentration of 50wt%, the flexural strength decreases by 63.6% compared to the composite without filler	Glass Fiber Reinforced Polymer (GFRP) material with varying ATH concentrations from 0wt% to 50wt%	[86]
Single flame retardant: Variations in MH composition	The flame retardancy of HDPE composites improves with an increase in the amount of MH added	The tensile strength of the composite with 50wt% MH decreases by 16.7% compared to the neat sample	High density polyethylene (HDPE) with varying MH compositions from 10wt% to 50wt%	[87]
Single flame retardant: Variations in APP composition	Flame retardancy improves, as indicated by a 71.7% reduction in the mass loss rate	Composites with APP show a 29% decrease in tensile strength compared to those without filler	Comparison of polylactic acid/polycarbonate/glass fiber composites with and without 10wt% APP	[88]
Combination of multiple flame retardants:	Both composites achieved UL-94 V-0 ratings. However,	The tensile strength of GFRP/ATH 100wt% is 73.2 MPa, while	Comparison between GFRP / ATH flame retardant composites	[89]

Methods or innovations	Flame retardancy	Mechanical properties	Additional information	Ref.
Combination of ATH and APP	GFRP/ATH 50wt%/APP 50wt% has a higher limiting oxygen index than GFRP/ATH 100wt%, with values of 43 and 33, respectively	GFRP/ATH 50wt%/APP 50wt% has a tensile strength of 73.1 MPa	with and without APP, specifically at ATH and APP compositions of 50wt% each	
Combination of multiple flame retardants: Combination of MH and APP	Flame retardancy increases with a rise in ATH or MH concentration	The tensile strength of PU with a combination of ATH 3.33%/APP 6.67% is higher than that of MH 3.33%/APP 6.67%, with values of 16.99 MPa and 10.59 MPa, respectively	Polyurethane (PU) with a combination of ATH 3.33%/APP 6.67% and MH 3.33%/APP 6.67%	[90]
Microencapsulation: Microencapsulate APP	Flame retardancy increases with the addition of microencapsulated APP in UP, as evidenced by the rising limiting oxygen index values of 22.3, 26.6, and 27.8 for concentrations of 10wt%, 20wt%, and 30wt%, respectively	UP composites with 20wt% microencapsulated APP show higher flexural strength (49.8 MPa) compared to those with 10wt% (48.6 MPa) and 30wt% APP (40.4 MPa), though all are still lower than neat UP, which has a flexural strength of 52.1 MPa	Variations in the concentration of microencapsulated APP in UP composites, ranging from 10wt% to 30wt%	[73]
Nanoparticle: Nano-sized ATH	The flame retardancy of the composite is determined by the flame size, with the epoxy composite containing 10wt% microsized ATH showing a higher flame size (12,000 pixels) compared to 10wt% nanosized ATH (6,500 pixels)	Nanosized ATH is claimed to produce better mechanical properties compared to microsized ATH due to the synergy of two different components	Comparing flame retardancy between micro-sized and nano-sized ATH in bisphenol-A composites	[91]

3. Ground Impact Resistance of Composite Battery Enclosures

Ground impact refers to the physical force exerted on a battery pack when a vehicle experiences a collision or an impact on the ground, such as hitting a pothole, speed bump, debris, or during an accident. In the context of EVs, the battery pack is typically mounted on the underside of the vehicle. Placing the battery pack beneath the passenger cabin floor offers protection against lateral impacts, simplifies maintenance, and supports battery swap technology implementation [92]. Furthermore, due to the increasing interest in the development of structural batteries, where multifunctional materials are desired [93], such ground impact resistance becomes extremely crucial. However, this positioning also makes it vulnerable to impacts that could damage battery cells, posing safety risks like short-circuiting, thermal runaway, or fires [58]. Therefore, understanding and mitigating the effects of ground impact is crucial for ensuring the safety and durability of EV battery packs. Research and development efforts focus on designing robust battery enclosures that can absorb and dissipate the energy from impacts, thus protecting the internal battery cells and maintaining the overall integrity of the battery system [94]. The battery pack enclosure, designed as an underbody shield made from hybrid composite carbon fiber material, successfully withstood the impact load from concrete speed bumps [95]. Battery enclosures are typically made of metals such as steel or aluminum. However, metal sheets with certain thicknesses are prone to denting upon ground impact. When these dents reach a specific depth and come into contact with lithium-ion batteries, they can trigger a dangerous thermal runaway. A promising concept to mitigate this risk is the addition of a ground impact barrier layer on the enclosure's surface. **Figure 3** illustrates this concept. In **Figure 3a**, the absence of a ground impact barrier allows the enclosure to press directly against the battery (highlighted in red), increasing the risk of thermal runaway. Conversely, in **Figure 3b**, the impact barrier layer absorbs the force, deforming without transferring energy to the main enclosure, thereby protecting the battery.

In crashworthiness research, thin-walled structures are well-known for their ability to absorb impact loads. Cross-sectional thin-walled shapes are employed in the design of battery enclosures to enhance their resistance to ground impacts. The thin-walled design allows for an optimal balance between structural strength and weight, ensuring that the battery enclosure can withstand significant impacts without adding unnecessary mass to the vehicle. By incorporating these reinforced shapes into the battery enclosure, manufacturers can improve the enclosure's ability to absorb energy from ground impacts, thereby protecting the battery cells from potential damage. This design approach not only enhances the safety and durability of the battery pack but also contributes to the overall structural integrity of the EV [96]. Efforts to enhance structural durability against ground impacts can be achieved through the design approach of using cross-sectional thin-walled shapes on the surface area of battery enclosures. Moreover, when designed using composite materials, the potential for weight reduction can be enhanced. A multi-cell thin-walled structure made from composite material, tested under quasi-static compression and dynamic impact, shows an increasing trend in energy absorption as the filling density increases [97]. An additional consideration in material selection is the environmental impact on structural performance. Material fatigue is heavily influenced by temperature gradients, which become more complex when applied to thin-walled structures [98]. Furthermore, when using adhesive joints between metal thin-walled structures and composite battery enclosures, humidity can also affect mechanical properties [99]. Both temperature and humidity should be taken into account when designing thin-walled composite battery enclosures.

As illustrated in **Figure 4**, the thin-walled structure with a hexagonal cross-section is positioned beneath the array of battery cells. Studies on these shapes are summarized in **Table 2**, supplemented with design variables, methods and findings. Followed by **Figure 5**, which illustrates the cross-sectional shapes of each thin-walled structure described in **Table 2**.

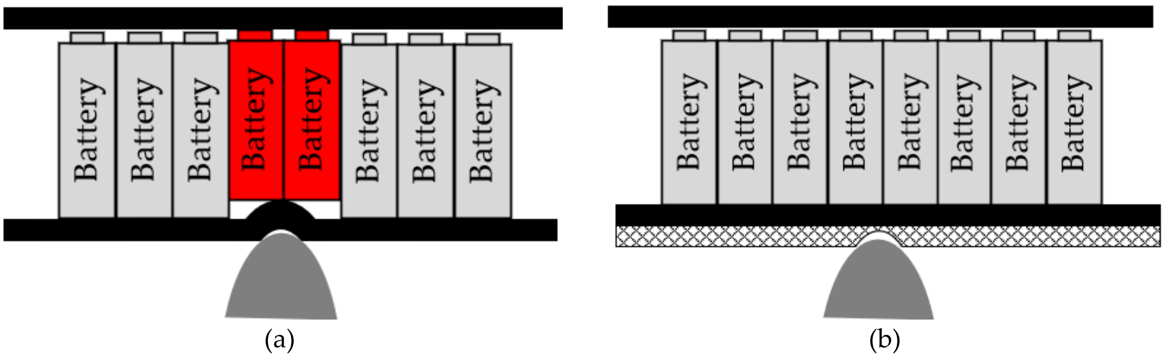


Figure 3. Illustration of the effects of ground impact on enclosures: (a) without a ground impact barrier, and (b) with a ground impact barrier

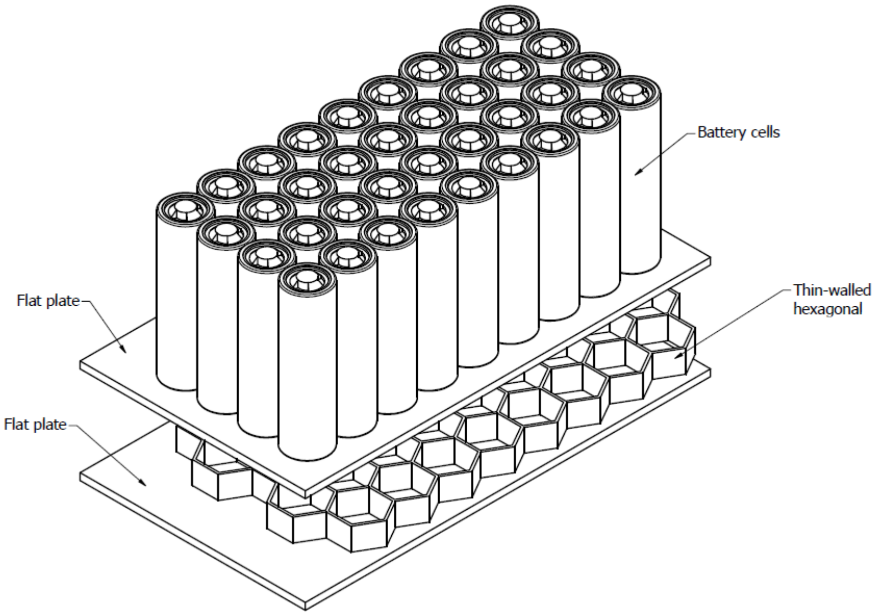


Figure 4. A thin-walled structure with a hexagonal cross-sectional shape is designed to withstand ground impact

Table 2. Cross-sectional thin-walled shapes

Cross-sectional name	Design variables	Methods	Findings	Ref.
Cylindrical	Crash absorbers with variations: cylindrical, square, hexagonal, and triangular	Simulation: explicit dynamic analysis	The cylindrical cross-sectional has demonstrated the highest crash absorption capability	[100]
Decagonal	Comparing the impact load resistance of decagonal, square, cylindrical, and hexagonal	Experimental: drop-weight impact test	The decagonal cross-sectional geometry shows the highest energy absorption	[101]
Multi-cell decagonal	Comparing the energy absorption of several multi-cell structures: hexagonal 3-cell, hexagonal 6-cell, and decagonal 10-cell	Simulation: quasi-static analysis	A decagonal 10-cell structure yields the highest energy absorption	[102]
Single-cell decagonal taper tubular	Comparison between conical, hexagonal, and decagonal single-cell taper tubular structures	Simulation: explicit dynamic analysis	The decagonal single-cell taper structure exhibited superior overall energy absorption efficiency	[103]
Multiple concentric decagonal tubes	Comparing the energy absorption of one to five tubes for each cross-sectional shape: cylindrical, hexagonal, octagonal, and decagonal	Simulation: quasi-static analysis	The decagonal structure with three tubes provides the highest energy absorption	[104]
Multi-cell circumferentially corrugated square tubes	Comparing the crashworthiness performance in terms of energy absorption and crushing force between	Simulation: explicit dynamic analysis	The crashworthiness performance of a square multi-cell structure with corrugations is superior to	[105]

Cross-sectional name	Design variables	Methods	Findings	Ref.
	traditional square multi-cell structures and circumferentially corrugated square multi-cell structures	Experimental: drop-weight impact test	that of traditional square multi-cell structures	
Multi-cell hierarchical hexagon honeycomb structure	Two hexagonal thin-walled structures with wall-to-wall cross-sectional design were compared to those with corner-to-corner cross-sectional design	Simulation: quasi-static analysis Experimental: constant speed compression	Hexagonal structures with wall-to-wall cross-sectional design exhibit higher energy absorption compared to corner-to-corner configurations	[106]
Octagonal multi-cell tubes	A comparison between thin-walled cross-sectional octagonal multi-cell structures with functionally graded thickness and those with uniform thickness	Simulation: explicit dynamic analysis Experimental: sled test	Thin-walled structures with octagonal multi-cell cross-sections and functionally graded thickness exhibit superior energy absorption compared to those with uniform thickness	[107]

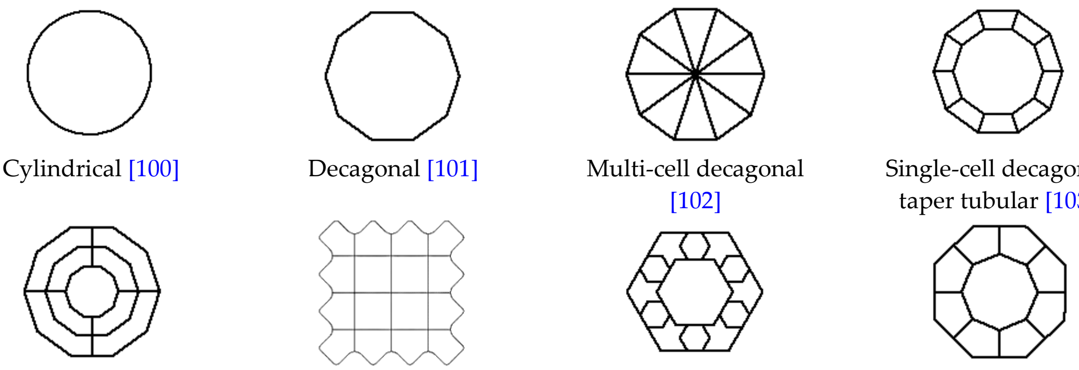


Figure 5. Cross-sectional diagram of the thin-walled structure as described in **Table** 2

Table 2 and **Figure 5** presents studies on cross-sectional shapes in thin-walled structures that can reinforce the surface area of Lithium-ion battery enclosures. The review results indicate that the decagonal cross-sectional shape is the most suitable design choice for mitigating potential ground impact loads on the battery pack. The decagonal cross-sectional shape exhibits the highest energy absorption compared to other shapes. However, when compared to dodecagonal (12-sides), the decagonal (10-sides) produces a lower initial peak crushing force [108]. This indicates that the decagonal is more effective in reducing the initial peak crushing force.

4. Lithium-Ion Battery Thermal Management

Effective thermal management is crucial for the performance and safety of Lithium-ion battery packs used in EVs. Lithium-ion batteries are highly sensitive to temperature variations, which can significantly affect their efficiency, lifespan, and safety [109]–[111]. Excessive heat can lead to thermal runaway, a dangerous condition where the battery overheats and can potentially catch fire or explode. Conversely, operating at low temperatures can reduce battery performance and capacity. Thus, thermal management systems are designed to maintain the battery within an optimal temperature range, ensuring reliable operation and enhancing overall battery life. These systems can be passive, relying on materials and design for heat dissipation [112]–[114], or active, using mechanisms like liquid cooling or air circulation to manage temperatures more dynamically [115]–[118]. A passive thermal management system operates without consuming external energy, while an active thermal management system requires external energy to generate heat transfer [119]. A combination of passive and active systems creates the so-called hybrid thermal management system, which is typically more complex in design but could compensate for the weaknesses of the standalone system [120]. When factoring in both mechanical and thermal properties together, multi-objective optimization methods can be applied when designing a battery pack. For example, a micro-channel cold plate with an embedded cellular structure is designed to provide more effective heat dissipation and mechanical stress distributions [121]. With the increasing adoption of EVs, advancements in thermal management technologies are critical to meeting the stringent safety and performance standards required for modern battery systems.

4.1. Passive Battery Thermal Management System

A passive battery thermal management system relies on the inherent properties of materials and design features to regulate the temperature of the battery pack without the use of active components like pumps or fans. This approach typically involves the use of phase change materials and thermal interface materials to dissipate heat generated during battery operation. Passive systems are generally simpler, lighter, and more energy-efficient than active systems, making them an attractive option for enhancing the safety and performance of EV battery packs. Passive thermal management using phase change material (PCM) is an attractive method due to its cost-effectiveness and ease of implementation [122]. PCMs help maintain an optimal and uniform battery temperature, preventing capacity degradation from high temperatures and poor performance from low temperatures. One PCM material particularly interesting for study is paraffin, known for its high latent heat capacity and low cost, making it an ideal heat absorbent material [123]. Paraffin is an attractive PCM due to its high latent heat, broad temperature range, low cost, favorable physical and chemical properties, low thermal hysteresis during melting, low vapor pressure, and minimal volumetric change during the phase transition [124]. Since paraffin is commonly available in powdered form, it can be used as a filler in composite systems, providing the advantage of ease of manufacturing similar to conventional composites. Studies related to the application of paraffin in passive thermal management are summarized in **Table 3**, along with methods and discussions of the findings from each study.

Parameters such as maximum temperature and temperature difference in a battery cell population, whether in a module or pack, are crucial. The maximum temperature reflects the safe operating limit of the battery cells under specific conditions, such as charge and discharge, while temperature difference indicates how effectively the addition of PCM has achieved uniform temperature distribution across each cell, impacting overall lifespan consistency. Studies in **Table 3** shows that paraffin-based PCM composites consistently achieve lower maximum temperatures compared to composites without paraffin. The typically low thermal conductivity of PCM can be significantly improved, such as the use of metallic framework [125]–[127], as well as by the addition of expanded graphite [128]–[131] or nanomaterials [132]–[134]. When combined with expanded graphite, these composites not only further reduce temperature but also improve temperature uniformity, offering valuable insights for thermal dissipation in battery design. However, it is also worth remembering that the use of paraffin might increase the overall risk of fire propagation and thermal runaway due to its flammability characteristic. Hence, it should be coupled with a sufficient fire protection system, either in the form of flame retardant material or other technologies.

Table 3. PCM composites for Lithium-ion battery enclosures

PCM	Important parameters	Thermal management methods	Findings	Ref.
1. Vinyl ester resin/paraffin 2. Vinyl ester resin/8-pentadecanone	• Latent heat • Battery temperature	PCM composites as enclosures for Lithium-ion 21700 cells	• The latent heat capacity of 8-pentadecanone is higher than that of paraffin, with values of 277 J/g and 212.8 J/g, respectively • The battery module with PCM composites of paraffin and 8-pentadecanone shows a lower maximum temperature of 32.5°C compared to 37.5°C for the module without PCM composites	[135]
Epoxy resin / paraffin / expanded graphite	Battery temperature	Three sheets of PCM composite were drilled to insert nine 18650 battery cells	At a charge and discharge rate of 2C: • The battery module with PCM composite shows a lower maximum temperature of 30°C compared to 48°C for the module without PCM composite • The battery module with PCM composite shows a lower temperature difference of 1.8°C compared to 14°C for the module without PCM composite	[136]
High-density polyethylene / paraffin / expanded graphite / carbon fiber	Battery temperature	The PCM composite, formed into a board, is attached to the sides of prismatic Lithium-ion battery cells	Batteries with high-density polyethylene/ paraffin/expanded graphite/carbon fiber composites provide better cooling effects, with a maximum temperature of 53°C compared to 55°C for paraffin/expanded graphite composites and 70°C for those without PCM	[137]
Paraffin / expanded graphite (EG)	• Latent heat • Thermal conductivity • Battery temperature	The molten PCM composite is poured to fill the gaps between battery cells inside the battery module	• The latent heat of the PCM composite with pure paraffin is 146.97 J/g, while the composite with an addition of 2.0% EG has a latent heat of 101.84 J/g; however, their thermal conductivities are 0.201 W/mK and 0.272 W/mK, respectively • At an ambient temperature of 50°C, the paraffin composite with 2.0% EG shows a lower maximum temperature of 70.3°C compared to 75.5°C for pure paraffin	[138]

4.2. *Active/Hybrid Battery Thermal Management System*

Different from the above, an active thermal management system for batteries typically involves the use of components such as cooling fans and heat pumps. These systems actively regulate the temperature of the battery pack by circulating a heat transfer fluid or air through channels or pipes within the battery enclosure. Regulating heat transfer using coolant fluids can maintain uniform temperature distribution [139]. By actively controlling temperature fluctuations, they help maintain optimal operating conditions for the battery cells, thereby enhancing the performance, longevity, and safety of the battery pack in EVs. Active thermal management in batteries aims to prevent uncontrollable thermal runaway by integrating estimation and monitoring, fault diagnosis, early warning systems, and equalization technology [140]. However, these benefits come with the drawback of increased energy consumption. Compared to passive thermal management systems based on PCM, active systems consume 22% more energy for the same vehicle range [141]. More complex systems, such as water jackets and heat exchangers, increase the maintenance costs of active thermal management systems [142], while passive thermal management systems that utilize air cooling through convection offer lower maintenance costs and eliminate the risk of liquid leakage into electronic components [143]. These innovations can be combined with PCM composites, forming a hybrid thermal management system. Such a design helps dissipate heat more effectively, both from the battery surface and the PCM itself, hence lowering the PCM recharge time. Publications on active and hybrid battery thermal management are presented in **Table 4**, showcasing innovations and findings from each study. **Figure 6** provides a comparison between a conventional, passive system and hybrid thermal management system for battery enclosures. In **Figure 6a**, the system utilizes a metal enclosure as a heat sink. The heat generated by the battery is directly transferred to the metal enclosure and then dissipated into the air through natural convection. This system could only be effective under a low heat dissipation rate from the battery cells; otherwise, some local hot spots could be found. In contrast, **Figure 6b** illustrates a hybrid thermal management system, where heat from the battery is absorbed by a PCM composite. The absorbed heat is then transferred to a circulating coolant through forced convection. The coolant is cooled down by a heat exchanger (not shown in the **Figure 6**). This hybrid system is more effective in dissipating heat compared to the previous approach. However, this improved heat dissipation in hybrid thermal management systems comes at the cost of increased energy consumption.

Table 4. Innovations in active/hybrid battery thermal management

Innovations	Thermal management methods	Findings	Ref.
Vortex generators	Forced air cooling system by varying winglet configurations in cooling channels	Incorporating vortex generators reduces both the maximum cell temperature and temperature differences within the cells	[144]
Vent plates	Forced air cooling system with a vent plate configured under prismatic lithium-ion batteries	The vent plate enhances cooling performance and promotes temperature uniformity across the batteries	[145]
Forced air cooling supplemented with U-shaped micro heat pipes	U-shaped micro heat pipes arranged between prismatic Lithium-ion batteries	The maximum temperature of the battery module is lower when using active air cooling with a U-shaped micro heat pipe array compared to without	[116]
Enhanced coolant medium in a liquid-based cooling system	Using hydrofluoroether as a coolant media	The battery cell temperature becomes more uniform	[146]
Enhanced coolant medium in a liquid-based cooling system	Using liquid metal as coolant media	The battery module's temperature is lower and more uniform with liquid metal compared to water	[147]
Mini-channel liquid-cooled	Varying the number of mini-channels	The maximum battery temperature can be controlled below 40°C if the number of mini-channels is above 4	[148]
Cold plates with PCM	Variations of fluid velocity and number of PCM plates	The power consumption and temperature nonuniformity can be notably reduced.	[149]

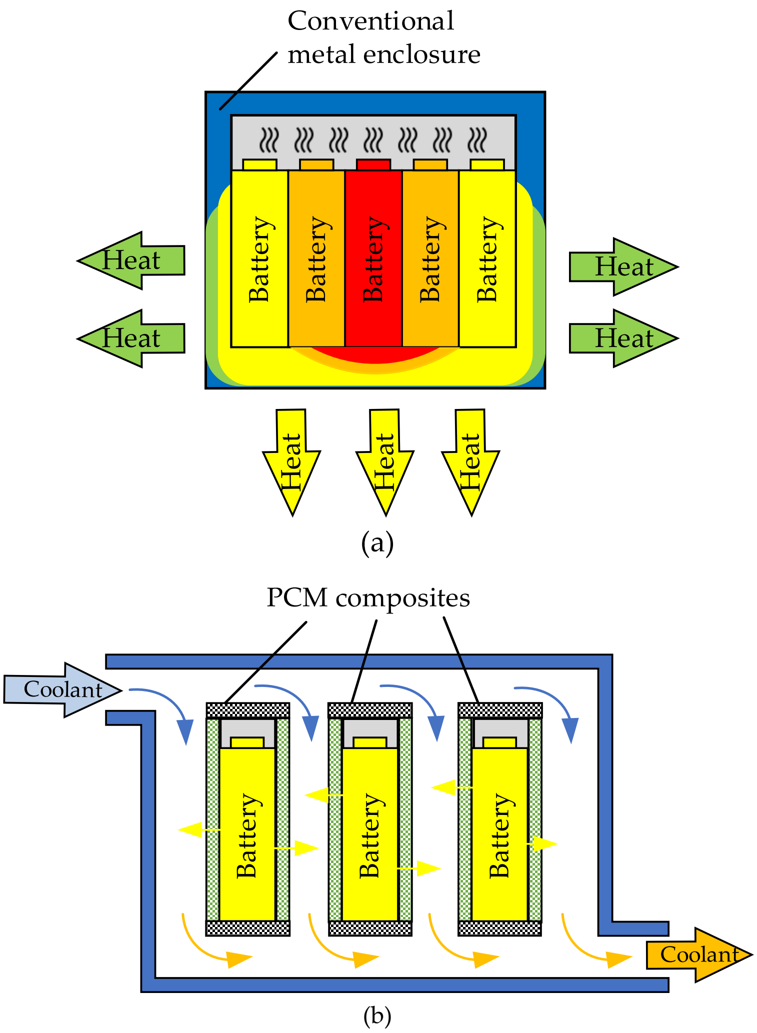


Figure 6. Comparison of thermal management systems: (a) conventional heat sink, and (b) hybrid PCM-air cooling system

Several innovations in active battery thermal management presented in **Table 4** aim to achieve lower maximum battery temperatures and reduced temperature differentials. In forced air cooling systems, innovation trends focus on shapes that generate vortex flows and enhance efficiency by adding heat pipes. In liquid-based cooling systems, improvements to the coolant media have increased battery cooling efficiency. Reviewing these studies can provide options for selecting thermal dissipation methods, especially during high charge and discharge operations. Lastly, the energy efficiency of the vehicle is also crucial, especially with the implementation of an active battery thermal management system.

5. Conclusion

Lithium-ion batteries are the cornerstone of modern electric vehicles (EVs), offering high energy density, long cycle life, and relatively low self-discharge rates. However, thermal runaway, a critical safety issue characterized by an uncontrollable temperature increase, can lead to fire or explosion. Ensuring flame retardancy is crucial in accident scenarios where the battery pack is exposed to an external fire. Additionally, battery packs face mechanical stresses and potential damage from ground impacts caused by debris or uneven road surfaces. Effective battery thermal management directly impacts capacity and longevity, underscoring the importance of research into flame retardancy, ground impact resistance, and thermal management, particularly in composite battery enclosures. Adhering to safety standards and regulations for Lithium-ion battery packs in EVs is essential for safe and reliable operation. Ensuring the flame retardancy of composite materials for Lithium-ion battery enclosures is crucial for the safety and reliability of EVs. Composites with multiple flame retardants outperform single-retardant systems, achieving a better balance between flame retardancy and mechanical properties. Methods such as microencapsulation and nanoparticle incorporation enhance flame retardancy compared to conventional commercial flame retardants. Reviews on flame retardants offer valuable insights for designing composite materials for Lithium-ion battery enclosures.

Ground impact refers to the physical force exerted on a battery pack during collisions or impacts with the ground, such as hitting potholes and debris, or encountering accidents. Mounted on the vehicle's underside, the battery pack is particularly vulnerable. Studies on cross-sectional shapes in thin-walled structures indicate that a decagonal shape is most suitable for mitigating ground impact loads, exhibiting the highest energy absorption.

Effective thermal management is essential for the performance and safety of Lithium-ion battery packs in EVs. Passive thermal management systems use materials and design features to regulate battery temperature without active components. Paraffin-based PCM composites consistently show reduced maximum temperatures compared to those without paraffin. When combined with expanded graphite, these composites improve both temperature reduction and uniformity, providing valuable insights for thermal dissipation in battery design. Active or hybrid thermal management systems use additional components like cooling fans and heat pumps to regulate battery temperature by circulating a heat transfer fluid through the battery enclosure. In forced air cooling systems, innovations focus on shapes that generate vortex flows and enhance efficiency with added heat pipes. In liquid-based cooling systems, improvements in coolant media have increased cooling efficiency. Reviewing these studies offers options for selecting thermal dissipation methods, especially during high charge and discharge operations.

Future specific studies could design a Lithium-ion battery enclosure using composite materials with multiple flame retardants, thin-walled decagonal cross-sections, and paraffin-based PCM composites for enhanced thermal dissipation. Thermal issues should be addressed numerically and verified experimentally, including external fire exposure and thermal dissipation during charge and discharge. The decagonal thin-walled structure can absorb impact energy like a crash box to prevent battery deformation, while the PCM composite maintains optimal and uniform battery temperatures. Such structures can also be developed from bio fibers to support the sustainability ecosystem. The general recommendations for future research and development include the advancement of battery enclosure materials capable of withstanding prolonged fire exposure, innovative structural designs to enhance ground impact resistance along with improved assembly methods for battery enclosures, and the development of efficient thermal management systems. These systems should effectively maintain optimal battery temperatures and support target temperature uniformity. Furthermore, to be able to effectively substitute existing automotive materials such as steel, the composite manufacturing processes and supply chains need to be significantly adjusted to meet the industrial demands. In terms of environmental impacts, a renewable energy source and recyclable, nature-based raw materials could be applied.

Author's Declaration

Authors' contributions and responsibilities

All authors contributed to the idea of the article. A literature search was performed by Sunarto Kaleg. The first draft of the manuscript was written by Sunarto Kaleg, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

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