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Experimental Investigation of Polymer Composite-Based Protective Structures for Mitigating Crash-Induced Mechanical Abuse in Lithium-Ion Batteries

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Abstract

The objective of this paper is to determine the effectiveness of using polymer composite protective structures to protect against the mechanical abuses associated with crash impacts that affect lithium-ion batteries in terms of their structural integrity and their overall safety. In addition to their use in electric vehicles, lithium-ion batteries are also being increasingly used in renewable energy-based energy storage systems because they have high energy densities, long lifetimes, and superior performance characteristics. As a result of their widespread use, it has become clear that there are major safety concerns with respect to their susceptibility to mechanical failure due to crash-induced mechanical abuse. Such mechanical failures can lead to internal shorts; structural deformations which can result in thermal instabilities; and reduced electrical performance. Therefore, this study investigated the use of advanced polymer composite materials to provide protection from mechanical failure when subjected to crash impacts. To achieve this goal, an extensive test program was developed to evaluate the effect of various types of polymer composite materials on the behavior of 18650 lithium-ion cells during drop and impact testing. Mechanical responses evaluated included impact energy, stress, strain, and displacement. Electrical response evaluations included changes in voltage, current, and state of charge, internal resistance and capacity retention. These evaluations examined whether polymer composites could be effectively used as lightweight absorbing materials to reduce the effects of crash induced mechanical loading. Additionally, these studies established a correlation between crashes induced mechanical loading and electrochemical degradation.

Keywords: Lithium-ion batteries (LIBs), polymer composite protective structures, crash-induced mechanical abuse, battery safety and crashworthiness, electro-mechanical performance degradation

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INTRODUCTION

Lithium-ion batteries have been identified as the most promising technology in electric vehicles, hybrid vehicles, and stationary storage systems because they are high in energy density, high in cycle life and they are high in efficiency [1–5]. However, with the high-paced evolution of electric vehicles, the safety concern of LIBs in the situations of mechanical abuse, and more so, in the conditions of crash, have become more important. As demonstrated in Figure 1, in actual accidents, LIBs are subjected to severe mechanical forces, such as impact, crushing and shock, which can cause deformation, short circuiting, thermal runaways, as well as degradation of a variety of electrical parameters [6–12]. Such mechanical conditions directly affect several battery parameters such as voltage stability, internal resistance, capacity retention, and State of Charge. The significance of the research lies in the fact that it is oriented on the investigation of the mutual behavior of mechanical and electrical parameters during crashes that is essential to battery safety and BMS enhancement.

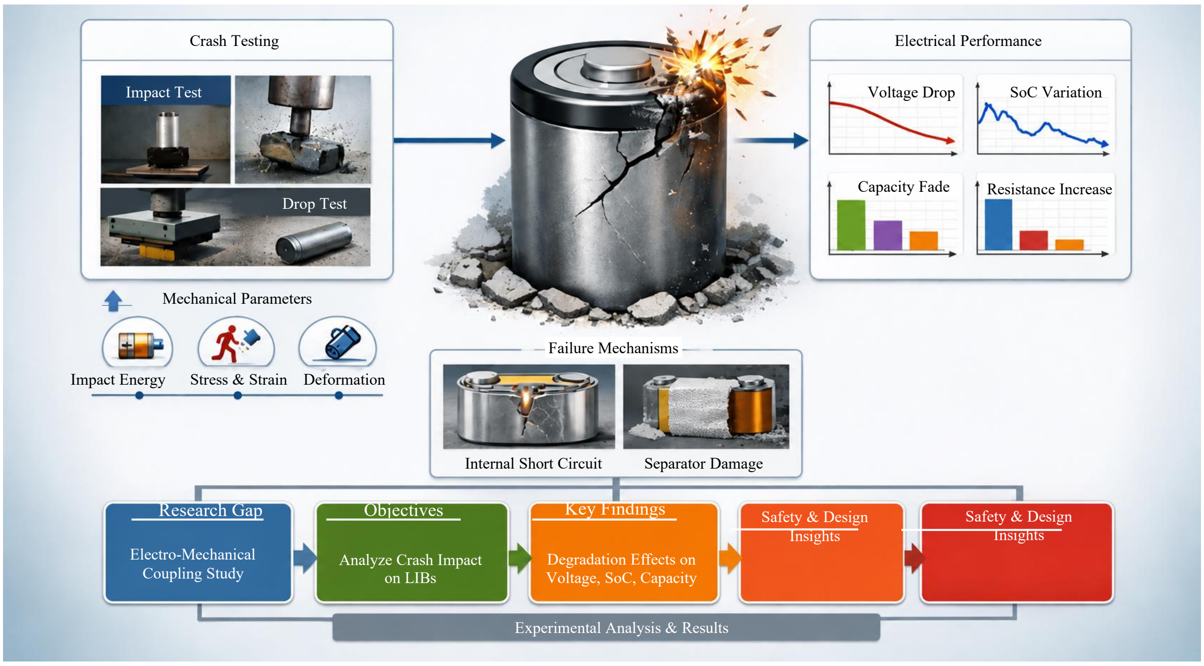

Figure 1. Crash-induced mechanical abuse and electrical performance degradation in lithium-ion batteries [1].

Various researchers have conducted detailed studies on either mechanical abuse testing of LIBs or degradation of LIB parameters under various conditions. Nevertheless, the combination of the two aspects using detailed experimental analysis has not been carried out [7–15]. Different literature reviews noted that the data on crash conditions is deficient, which results in numerous mechanical parameters such as stress, strain, and displacement, as well as changes in LIB parameters such as voltage stability, internal resistance, capacity retention, and State of Charge. In a bid to fill this gap, this research recommends experimental research on the effect of mechanical abuse in the form of drop and impact loading on electrical performance of lithium-ion batteries [16–20]. These aims are to investigate the relationship between mechanical stress and electrical degradation, to identify the important degradation processes and to quantify the changes in voltage, internal resistance and capacity before and after mechanical testing. Moreover, the proposed analysis is also supposed to be useful in developing new and better safety concepts and predictive maintenance methods. The research seeks to find a direct relationship between mechanical abuse due to the crash and electrical performance degradation of lithium-ion batteries using a hybrid experimental and data-driven method [21–25].

ROLE OF POLYMER AND COMPOSITE MATERIALS IN BATTERY PROTECTION

The use of polymer and composite materials has proven to be essential in increasing the strength, crashworthiness and longevity of Lithium-Ion Batteries that are used in Electric Vehicles [26, 27]. The primary function of the polymer separator is to provide electrical isolation with the capability of allowing ions to pass from one electrode to another thus eliminating internal shorts. Polyethylene (PE), polypropylene (PP), and polyvinylidene fluoride (PVDF) are examples of polymer separators [28–31]. The polymer binder provides adhesion between electrodes providing both mechanical stability and maintaining electrode structure throughout battery operation. Thermoplastics and thermosets can be formed into advanced composites which can be utilized as lightweight and strong enclosures for the battery [32, 33]. Carbon-fiber-reinforced polymers (CFRP) and glass-fiber-reinforced polymers (GFRP) possess high levels of stiffness and impact resistance at reduced weights compared to other composites; they also serve well for protecting battery packs. Aramid fibers are used as composites to provide improved energy absorption and damage tolerance when subjected to crash loads. Shear-thickening polymer composites can dissipate impact energies by developing strain-rate dependent hardening behaviors. Additionally, foam-based polymers are widely used as cushioning and damping materials to reduce stress transmitted to individual battery cells [34, 35]. Recent studies have focused on using composite materials inspired by nature, specifically those with cellular architectures, like natural materials, which exhibit extraordinary crash energy absorption with low weights. Overall, it is clear that polymer and composite materials will continue to play a major role in reducing crash-induced mechanical stresses to battery systems and promoting structural integrity to ensure the continued safe performance and reliability of Lithium-Ion battery systems in electric vehicles.

LITERATURE REVIEW

Significant research has been conducted to study the performance of LIBs under mechanical abuse conditions, focusing on safety, failure, and degradation characteristics. Recently, research in the area has been directed towards understanding the consequences of mechanical abuse, including penetration, crushing, etc., which can lead to internal short circuits, heat generation, and emission of hazardous gases. For instance, Nair et al. [1] conducted a review on the performance of LIBs under nail penetration and thermal abuse, focusing on the emission of gases, while Sheikh et al. [2] conducted a study on the performance of LIBs under crash conditions, including voltage instability, internal damage, etc. In addition, the structural protection approach has been studied, including the performance of bio-inspired cellular structures, as demonstrated in the research conducted by Dabasa et al. [3], while Dong et al. [4] demonstrated the performance of shear-thickening materials. Advanced modeling techniques have been utilized to study the performance of LIBs under crash conditions, including the research conducted by Ma et al. [5], in which machine learning has been integrated with finite element analysis to predict the performance under crash conditions, while earlier research conducted by Wierzbicki et al. [10–12] demonstrated the performance of LIBs under abuse conditions, including electrochemical, thermal, and mechanical modeling, while Marcicki et al. [7] and L'Eplattenier et al. [8] demonstrated the performance of LIBs under abuse conditions using LS-DYNA simulations, while Zhu et al. [6] demonstrated the performance of LIBs under mechanical indentation, which can lead to capacity loss due to electrode damage. In addition, probabilistic risk assessment has been conducted to improve the performance of LIBs under crash conditions, including the research conducted by Mustaffa, Z. et al. [9], while optimization techniques, including battery pack optimization, have been demonstrated in the research conducted by [17, 19], while the research conducted by [13–16]. demonstrated the performance of LIBs under abuse conditions, focusing on safety, including fire suppression, early failure, electrical hazards, etc. However, most of the research conducted has been focusing on either structural integrity or electrochemical-thermal performance, while the correlation of mechanical parameters under crash conditions with the performance degradation of LIBs has not been conducted, which forms the motivation behind the experimental investigation conducted in the current research.

Summary of Existing Research

In the case of lithium-ion battery (LIB) abuse, the existing literature on the topic is primarily focused on the failure mechanisms, safety issues, and structural integrity under crash conditions. The literature, as presented by Nair et al. [1] and Sheikh [2], indicates that abuse conditions, such as penetration, crash, and crushing, may result in short circuit, thermal instability, and electrical instability. The experimental investigations, as presented by Zhu et al. [6], indicate the capacity fading and increased internal resistance, caused by the deformation and damage to the electrodes. On the other hand, the simulation-based investigations, as presented by finite element analysis (FEA) and multi-physics simulations [5, 10–12], have shown the stress, deformation, and coupled electrochemical and thermal effects. Moreover, the existing literature is also focused on the battery protection designs [3, 4, 17, 19], safety strategies [13, 15, 16], and system-level risk assessments [9, 20], to enhance the crashworthiness and reliability of the battery pack in EVs.

Comparison of Methods

The methodologies adopted in previous studies can be categorized into three main categories, namely, experimental, computational, and hybrid approaches. Experimental approaches, such as drop, impact, nail penetration, etc., give a realistic picture of material failures and degradation in electrical properties, although they are often associated with a high cost, safety hazards, and non-repeatability. On the other hand, computational approaches, such as FEA and LS-DYNA, give a detailed picture of stress, strain, and deformation under controlled conditions, depending on the accuracy of underlying models and assumptions. Similarly, hybrid approaches, such as machine learning and simulation, improve prediction accuracy and flexibility through a combination of data-driven and physics-based approaches such as those adopted in [5]. Although [4, 17–19] focus on protective materials and structural optimization approaches, respectively, safety-oriented approaches often consider thermal management and mitigation, as in [13, 15].

Identified Gaps

Although a tremendous amount of research has been conducted on Li-ion batteries, there exist a few gaps in previous studies, which are critical and important for developing a new approach. Most studies consider mechanical, thermal, and electrical properties individually, without considering electro-mechanical coupling effects during a crash event. Similarly, a complete set of experimental data, considering mechanical properties, such as stress, strain, and deformation, along with corresponding electrical property variations, has not been adequately addressed in previous studies. Furthermore, real-time monitoring and correlation of damage due to a crash event with electrical degradation are also not adequately addressed in previous studies. Similarly, models and approaches, such as those presented in [4, 17, 19], are often not validated through combined approaches and standardized testing protocols for crash events, which are critical and important for developing a new approach.

Problem Statement

The lithium-ion batteries in electric cars are extremely prone to mechanical abuse during the crash events resulting in structural damage, internal short-circuits and loss of key electrical parameters like voltage, internal resistance, and capacity. The major issue that has been tackled in this paper is that there is no clear and quantified knowledge on the direct relationship between crash-induced mechanical stresses and electrical performance. This is significant since failure of the battery during crashes may lead to safety risk, low reliability, and poor performance of the system. Current methods are largely based on either mechanical behavior (by crash tests) or electrochemical degradation (by electrical tests), and there has been little combination of the two fields. Also, present models do not have adequate experimental validation and do not offer real-time correlation of mechanical damage and electrical response, which poses an important gap in predictive safety assessment.

Application of Polymer and Composite Materials to Improve Safety, Reliability, and Performance of Lithium-Ion Batteries in Electric Vehicles

Polymer and composite materials are being employed with increasing frequency in the field of battery protection due to a combination of unique physical properties which include: a relatively low mass; an excellent mechanical property profile; excellent energy absorption profiles; and multifunctional properties [20, 26]. For example, carbon-fiber reinforced polymer (CFRP) battery enclosures have been identified as potential solutions to reduce vehicle weight while maintaining structural integrity and crash-worthiness. Glass-fiber reinforced polymer (GFRP) impact shields also provide a cost-effective solution to crash protection by providing enhanced impact resistance and structural durability. Aramid fiber composites have been researched to take advantage of their exceptional toughness and energy absorption profiles to mitigate the effects of damage when subjected to extreme mechanical loads. In addition, polymer foams are commonly used as vibration-dampening or cushioning materials to help dissipate the stresses caused by vibrations that could be transmitted from the vehicle structure to the individual battery cells [27, 28]. New shear-thickening polymer composites have been developed and researched as a means to efficiently absorb the impact energies generated during a crash event. Finally, new nanocomposite coating materials, such as those incorporating graphene, carbon nanotubes and ceramic particles, have shown improved thermal management and flame-retardant properties [29–32]. Self-healing polymers represent another recent development in polymer composites, these types of polymers have shown the ability to autonomously heal micro-cracks within the material which will potentially extend the useful service life and improve the overall safety of lithium-ion batteries for electric vehicles.

The selected polymer composite materials (CFRP, GFRP, Kevlar / epoxy laminate, shear thickening polymers, PU foam, honeycomb) possess the appropriate properties of light weight and good impact and structural durability that make them suitable for use in automotive battery pack applications. Additionally, due to their respective combinations of stiff to weight ratios, toughness to absorb energy and to resist deformation, PU foam and honeycomb also act as effective dampeners of vibrations and protectors against crashes. Shear thickening polymers also provide an ability to adaptively reduce or eliminate impact during a dynamic load event. In addition to providing impact reduction capability, all these materials can help improve battery safety by helping to distribute stress throughout the material and/or preventing mechanical failure during crash events.

PROPOSED METHODOLOGY

In this research (refer to Figure 2), the investigator hypothesized that the proposed experimental framework is used to examine the effects of mechanical abuse on the electrical performance of lithium-ion batteries caused by crashes. The methodology is to perform controlled drop and impact testing and then perform electrical characterization of the pre-test and post-test conditions. The system model comprises three phases: (i) mechanical testing to measure stress, strain, and deformation variables, (ii) electrical performance analysis with voltage, current, state of charge (SoC) and internal resistance, and (iii) correlation of mechanical and electrical responses. The methodology uses both experimental measurements and simulation insights (FEA-based stress analysis) to make sure that it is thoroughly evaluated. The most important analysis models are regression-based relationships and statistical analysis to determine the trends of degradation. Mathematically, the experiment connects mechanical input measures (e.g., impact energy, $E = mgh$) with electrical degradation measures (e.g., capacity fade, resistance increase) to facilitate an ordered realization of the electro-mechanical interaction of crash conditions.

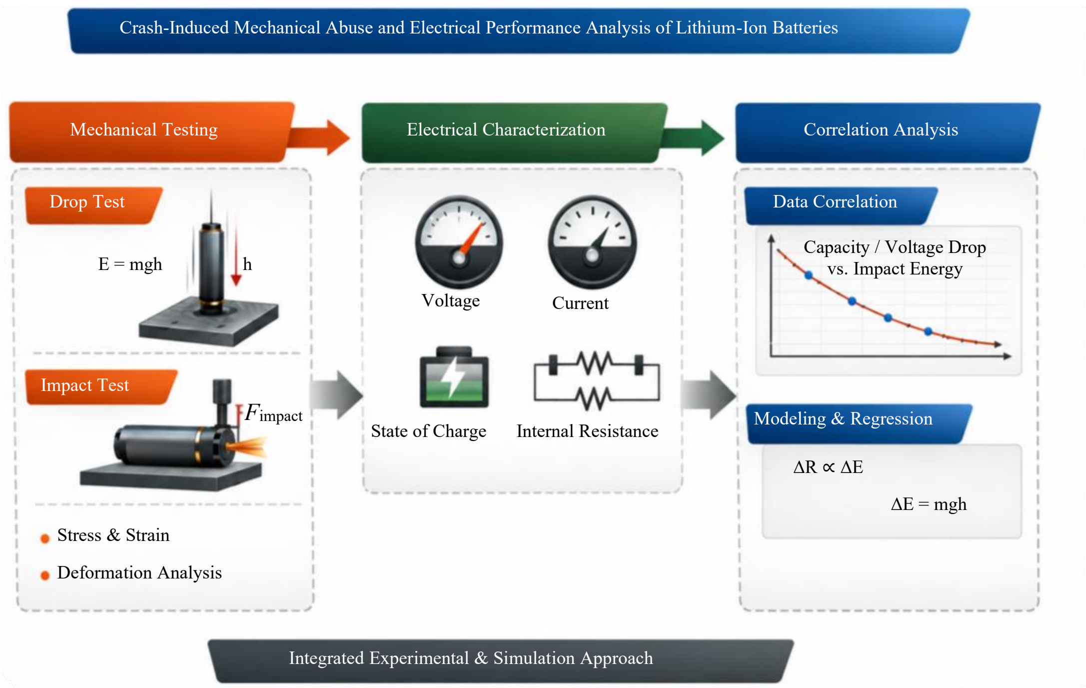

Figure 2. The proposed methodology of crash induced mechanical abuse and electrical performance analysis of lithium-ion batteries [4].

IMPLEMENTATION/EXPERIMENTAL SETUP

This study will be implemented using both experimental and data-driven analysis to explore the impact of mechanical abuses on crashes on the performance of lithium-ion batteries. The data and tools employed in this experiment are comparable to the ones discussed in the attached report. In this study, it is demonstrated that different tools, hardware and software, are employed to conduct experiments and simulations. Hardware devices applied in this experiment are drop tester, impact tester, battery cycler, digital multimeter, impedance analyzer, thermal imaging camera and vibration tester. The simulation tools applied in this experiment are a set of tools, such as SolidWorks, which are used in the simulation of stress, strain, and deformation.

As depicted in Figure 3, the data sets in this study include mechanical and electrical parameters obtained before and after the drop and impact tests that were performed on lithium-ion cells, which are primarily of 18650 form factors. The mechanical parameters measured during this experiment include drop height, impact velocity, von Mises stress, displacement, and equivalent strain. The electrical parameters measured during this experiment include voltage, current, and state of charge, capacity, and internal resistance. The data sets also contain various observations made during experiments, including leakage, damage, and thermal behavior. The parameters used for this analysis are mechanical parameters such as impact energy, stress (upto 10^9 N/m²), strain, displacement, drop height, and velocity. The electrical parameters are voltage variations, capacity fade (2.5 Ah to 2.3 Ah), energy loss, change in internal resistance, and SoC variations. The environmental parameters are temperature variations (0°C to 45°C) and test condition parameters based on IEC and UN standards. This analysis was carried out in an experimental setup in a controlled environment, and a battery testing chamber was used. Simulation was conducted with the FEA software, and the material properties are aluminum casing and nickel caps used in this analysis. These parameters are modeled and tested to guarantee correct determination of mechanical and electrical parameters to be analyzed on crash induced battery behavior.

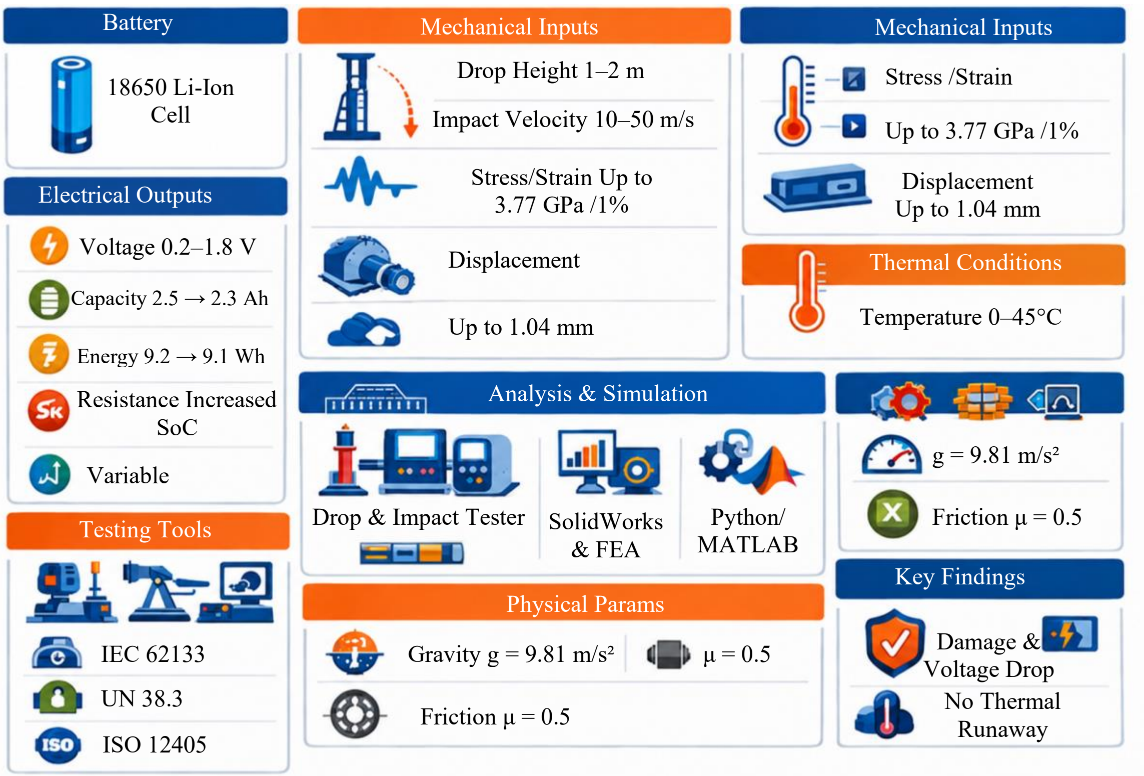

Figure 3. Experimental set up framework.

The drop and impact test methodologies used in this research were chosen to represent typical mechanical misuse conditions found in vehicular crashes, battery mishandling incidents and road-

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induced impact incidents. The selected drop heights and corresponding velocity and load conditions are likely to create stress and deformations that will be like those experienced by batteries as determined in crashworthiness tests of batteries and referenced in current safety standards worldwide. Although it is unlikely possible with laboratory testing to recreate the total complexity of actual vehicular crashes which involve multi-axial loads; thermal loads; and interaction at the pack level, the experimental methodology established here presents a controlled and reproducible means to evaluate the degree to which an automotive battery is vulnerable to mechanical misuse and assesses the capability of various materials to provide protection against such use.

Polymer Composites, as Table 1 shows, that offer high levels of protection (CFRP, GFRP, Kevlar/epoxy, Shear-Thickening Polymers, PU foam, Honeycomb) will be able to protect lithium-ion batteries from impact by absorbing impact energy in addition to reducing the amount of stress transmitted through the cell and reducing deformation. Protected battery cells are expected to have less stress concentration than unprotected cells. Also, protected cells should demonstrate improved voltage stability. Finally, protected cells should experience a slower increase in internal resistance and longer retention of capacity after an event. Additionally, many of these composite materials offer both structural support and multi-functionality with respect to thermal management and safety; therefore, they may serve as excellent candidates for next generation electric vehicles.

Table 1. Polymer composite protective materials and their expected influence on battery performance [26–34].

Protective Material	Type	Primary function	Expected influence on battery performance
CFRP	Composite	Structural enclosure	Reduces stress and deformation, improves crashworthiness and capacity retention.
GFRP	Composite	Impact shield	Enhances impact resistance and voltage stability while reducing mechanical damage.
Kevlar/Epoxy	Composite	Energy absorption layer	Minimizes crack formation, improves safety, and lowers internal resistance growth.
Shear-thickening Polymer	Functional Polymer	Impact mitigation	Absorbs high impact energy through strain-rate hardening, reducing cell damage.
PU Foam	Polymer	Cushioning and vibration damping	Reduces shock transmission, deformation, and thermal stresses.
Honeycomb polymer Composite	Composite	Crush-resistant structure	Provides high energy absorption, improved thermal stability, and enhanced battery protection.

Characterization, as Table 2 shows, is critical to understanding the mechanical, thermal, chemical, and physical (structural) characteristics of the materials that protect batteries from damage in a crash or fire event. Characterization is also needed to determine how changes in the material composition affect its crashworthiness performance.

Table 2. Characterization of protective polymer composites [26–34].

Technique	Purpose	Information obtained
SEM	Surface morphology analysis	Cracks, fiber distribution, damage patterns.
FTIR	Chemical characterization	Functional groups and bonding interactions.
XRD	Structural analysis	Crystallinity and phase identification.
DSC	Thermal transition analysis	Glass transition and melting behavior.
TGA	Thermal stability evaluation	Degradation temperature and weight loss.
Impact Testing	Mechanical characterization	Energy absorption and impact resistance.
Compression Testing	Structural evaluation	Compressive strength and deformation behavior.

Table 3 shows the application of advanced polymer composite strategies for battery protection has integrated four key areas to improve crashworthiness, thermal management, durability, and environmental sustainability of the battery protection system; these include structure-property optimization, nanocomposite reinforcement, surface engineering, and sustainable material solutions. The impact of structural parameters (e.g., fiber orientation, matrix type, and filler loading) on the ability of the composite to absorb energy and perform mechanically can be improved. Nanoscale reinforcements based upon graphene, carbon nanotubes (CNTs), MXenes and nanoclays have been shown to have multifunctional benefits as fillers by improving mechanical performance through stiffening, enhancing flame retardancy through char formation, increasing electrical conductivity for enhanced heat dissipation and protecting against corrosion. In addition, surface engineered approaches will continue to increase the effectiveness of composite battery protection systems through improvements in adhesion between the composite and substrate, therefore, protecting the underlying components. Sustainable solutions including recyclable thermoplastic matrices, biodegradable polymers and natural fiber reinforced composites will enable the continued development of environmentally sustainable battery protection systems for electric vehicles.

Table 3. Advanced polymer composite strategies for enhanced battery protection [26–34].

Strategy Category	Material/parameter	Key function	Benefits for battery protection
Structure–Property Relationship	Fiber Orientation	Controls load transfer and stress distribution	Improved energy absorption and reduced deformation.
	Matrix Type	Determines toughness and thermal stability	Enhanced crash resistance and durability.
	Porosity	Reduces weight and influences impact response	Lightweight structures with improved protection.
	Layer Thickness	Controls impact attenuation	Increased crashworthiness and structural integrity.
	Filler Loading	Reinforces composite matrix	Improved strength and thermal conductivity.
Polymer Nanocomposites	Graphene/Polymer Composite	Mechanical and thermal reinforcement	Enhanced impact resistance and heat dissipation.
	CNT/Polymer Composite	Conductive reinforcement	Improved mechanical strength and electrical performance.
	MXene/Polymer Composite	Multifunctional enhancement	Superior thermal management and energy absorption.
	Nanoclay/Polymer Composite	Barrier and structural reinforcement	Increased stiffness and thermal stability.
Surface Engineering	Surface Modification	Tailors surface properties	Improved durability and wear resistance.
	Adhesion Mechanisms	Enhances interfacial bonding	Reduced delamination and improved load transfer.
	Interface Engineering	Optimizes material interactions	Better structural integrity and safety.
	Functional Coatings	Provides protective layers	Improved thermal, corrosion, and impact resistance.
Sustainable Polymer Solutions	Recyclable Thermoplastics	Material recovery and reuse	Reduced environmental impact.
	Biodegradable Polymers	Eco-friendly material alternative	Sustainable battery protection systems.
	Natural-Fiber Composites	Renewable reinforcement materials	Lightweight and environmentally friendly structures.
	Circular Economy Strategies	Resource optimization	Reduced waste generation and improved sustainability.
	Life-Cycle Assessment (LCA)	Environmental impact evaluation	Sustainable material selection and design.

RESULTS AND DISCUSSION

The results obtained from the experimental and simulation analysis provide a comprehensive understanding of the effects of crash-induced mechanical abuse on the structural as well as the electrical performance of the lithium-ion battery.

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Mechanical Response Under Drop and Impact Conditions

The change in the mechanical parameters due to the increase in drop height is depicted in the graphs shown in Figures 4, 5, and 6. As can be seen, the value of von Mises stress increases considerably due to the increase in drop height, which indicates the severity of the mechanical stress in the battery due to crash conditions. In addition, the displacement and strain values show a gradual increase, which indicates the deformation in the battery due to mechanical stress. As can be noted, the relationship between the impact velocity and stress, as depicted in Figure 7, indicates an increase in stress due to an increase in the impact velocity, which reaches the maximum value under high-velocity conditions which is consistent with findings reported in [5, 10]. As can be noted, the results obtained from the simulation analysis are in close agreement with the results obtained in the prior study, which indicates the effect of crash conditions on the battery. This stress increment trend with drop height is explained by the corresponding increment in impact energy (E = mgh) that causes an increment in force transmission to internal battery part, causing structural deformation.

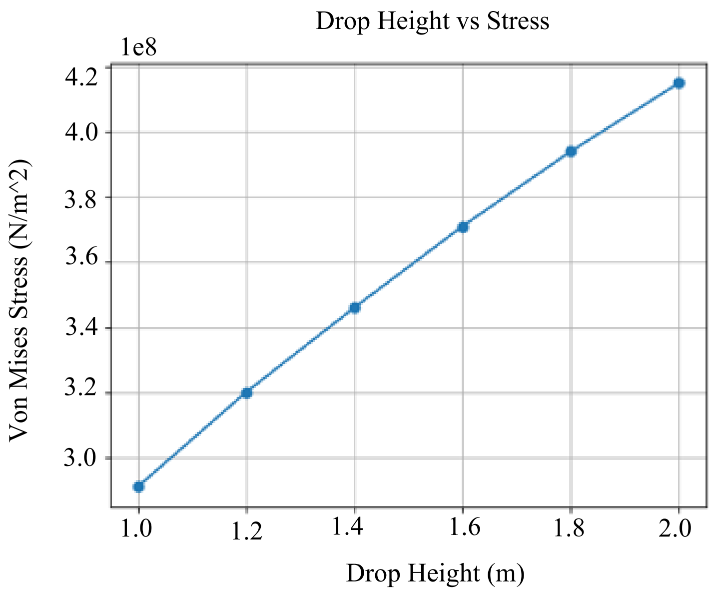

Figure 4. Drop height vs. stress.

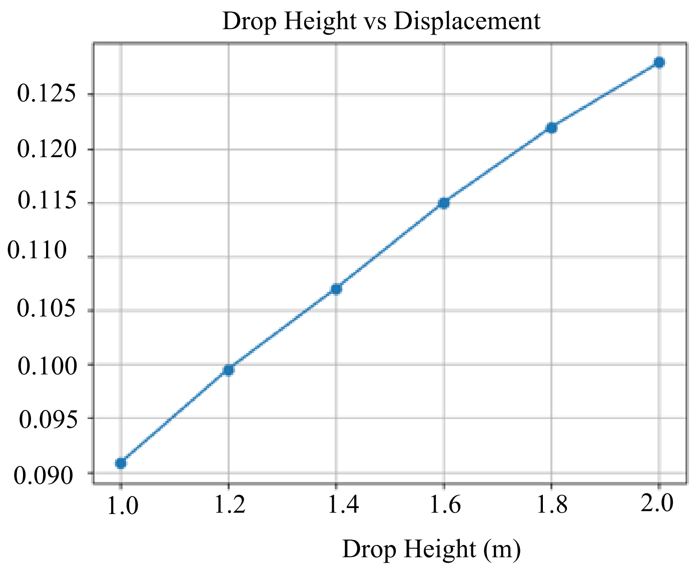

Figure 5. Drop height vs. displacement.

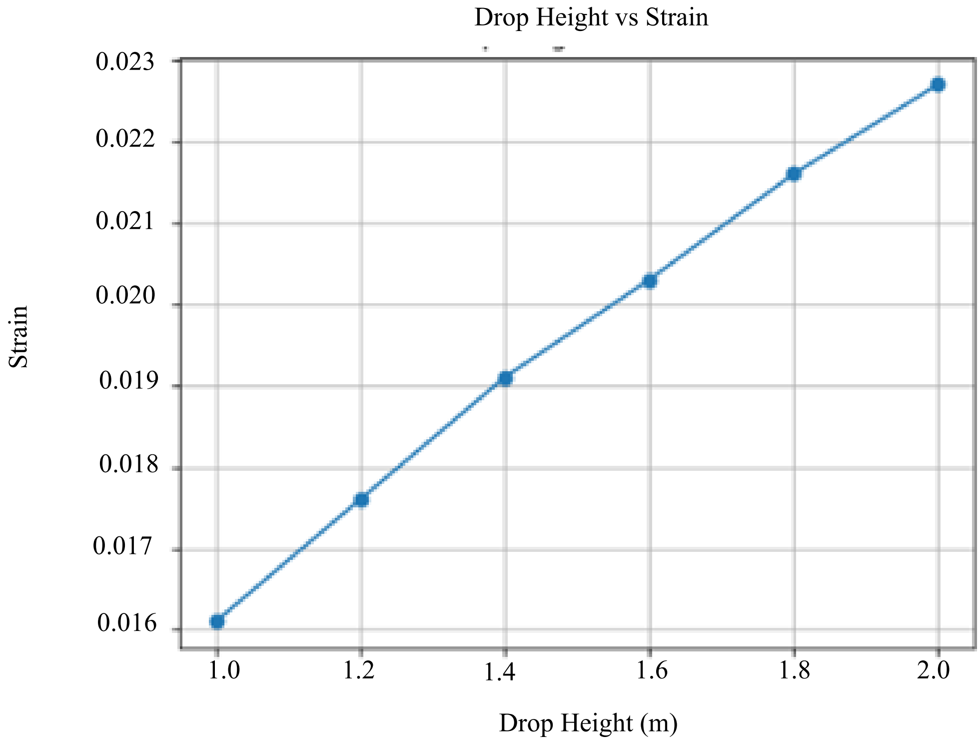

Figure 6. Drop height vs. strain.

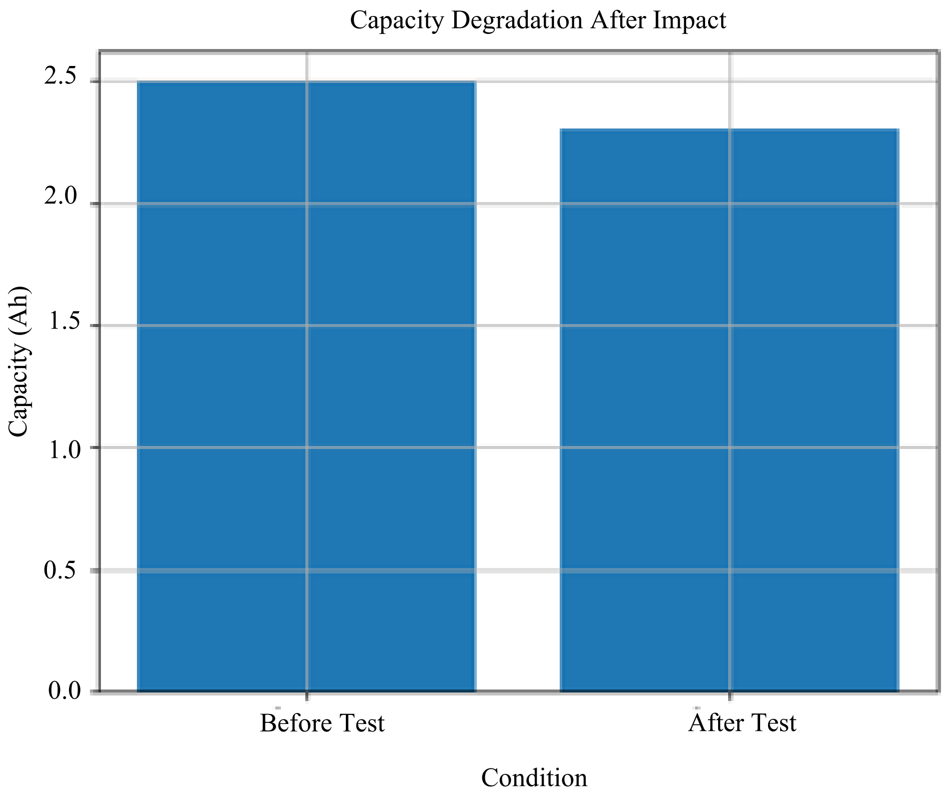

Figure 7. Capacity degradation after impact.

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Polymer composite structural designs have several elements that influence how well they can absorb energy from an impact event; in particular, the design of the structure itself (i.e., architecture) plays the most important role in determining the amount of energy absorbed during the impact. Impact loads induce kinetically-induced damage (deformation, fiber breakage, matrix crack initiation, etc.) within each layer of a polymer composite. A combination of layer thicknesses and fiber orientations will also determine when a first layer fails locally or otherwise, which ultimately influences how much energy is absorbed throughout the entire structure. For example, it has been shown previously that Kevlar/epoxy and honeycomb structures both demonstrate better overall energy absorption than all other materials tested because of their inherent ability to absorb higher levels of load prior to local failure and/or because they are able to spread out stress concentrations across a greater surface area than the other materials. Additionally, shear-thickening polymers were found to exhibit adaptive impact behavior as they increase their own stiffness with increases in strain rate. All the aforementioned mechanisms contribute to reducing the magnitude of peak stress transmitted to the Li-Ion battery cells and, therefore, help to maintain electrochemical function.

Electrical Performance Degradation

The performance of the battery before and after the mechanical abuse is depicted in Figure 8, which indicates a reduction in the capacity from 2.5 Ah to 2.3 Ah, which indicates the degradation in the battery due to mechanical stress. In addition, the voltage variations, as depicted in Figure 9, indicate a sharp reduction in voltage due to mechanical stress, which indicates the degradation in the battery due to mechanical stress. These observations are in accordance with the existing literature, where an increase in internal resistance, as also reported in [6, 10–12] reduction in ion transport efficiency, and capacity loss are reported due to mechanical deformation. The capacity degradation is believed to be due to the electrode microcracking and loss of active material, which decreases the efficiency of lithium-ion diffusion. Also, the deformation of the separators and localized short-circuit routes can lead to higher internal resistance.

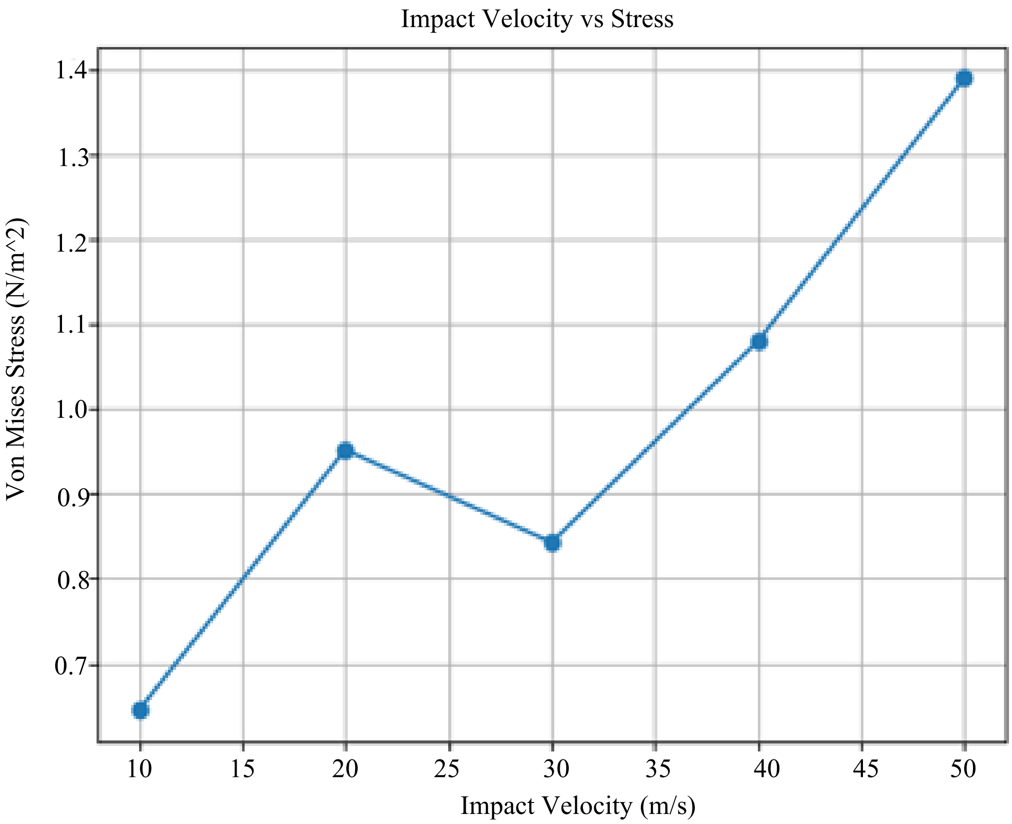

Figure 8. Impact velocity vs. stress.

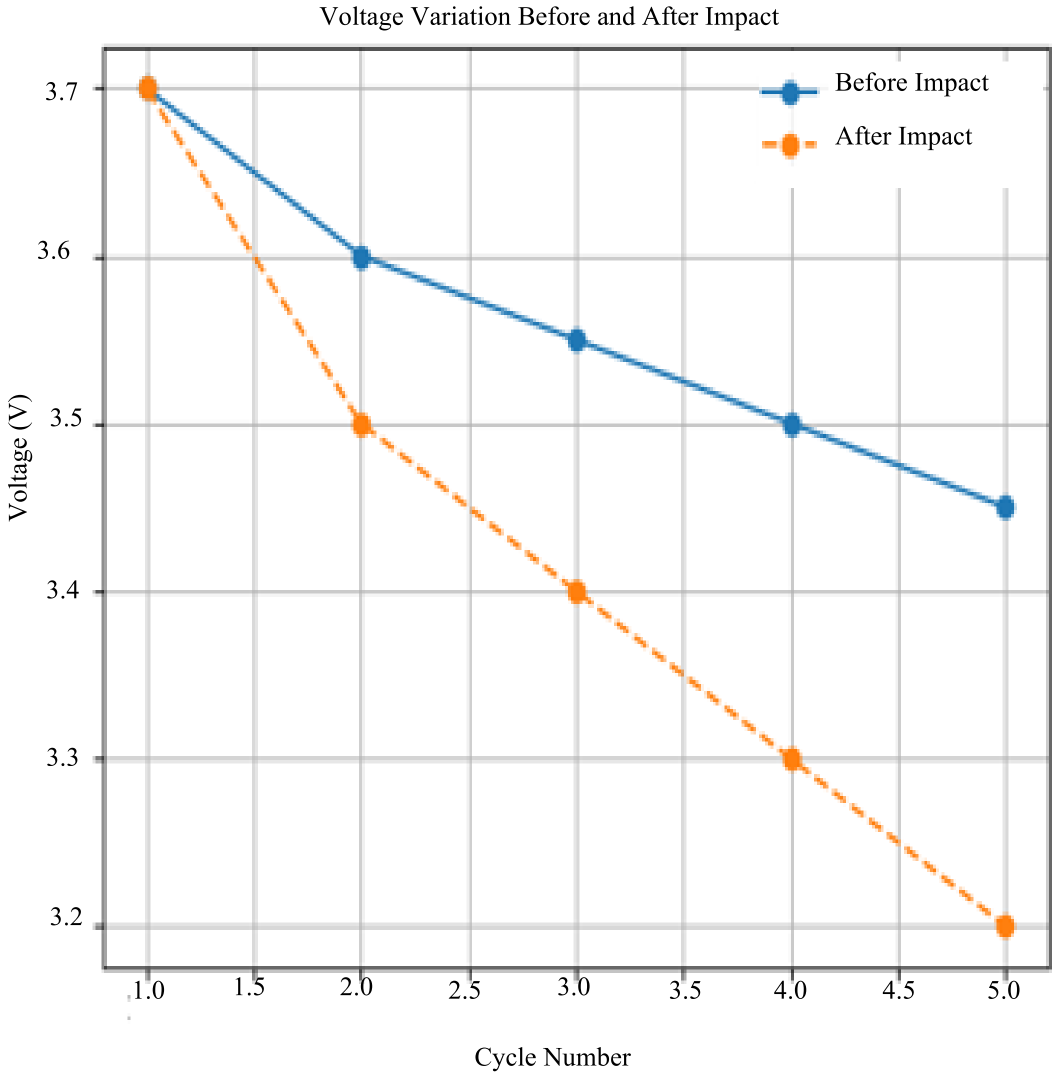

Figure 9. Voltage variation before and after impact.

Electro-Mechanical Coupling Analysis

The relationship between stress and electrochemical degradation is shown in Figure 10. Capacity loss is observed with an increase in stress. This figure clearly explains the electro-mechanical coupling effect. Moreover, the 3D relationship in Figure 8 explains the impact of stress and displacement on capacity loss. This multi-parameter analysis is used to understand battery failure. This analysis is more realistic compared to the conventional method of analyzing each parameter individually, especially when considering crash scenarios similar electro-mechanical coupling behavior has been observed in previous studies [10–12]. This assembly suggests that power-driven pressure directly disturbs interior electrochemical directions, henceforth, pretty deprivation kinetics once exposed to active forces.

Machine Learning-Based Prediction Analysis

In this section, the predictive analysis of the machine learning-based model is performed using Figures 11–14. Figure 12 is the plot of actual and predicted capacity. The high accuracy of the model is confirmed. Figure 13 is the residual error plot, confirming the consistency of the machine learning-based model. Moreover, Figure 14 is the regression fit plot, confirming the effectiveness of the machine learning-based prediction. The high predictive success indicates that the chosen mechanical parameters play a major role in battery degradation, which justifies the appropriateness of machine learning in predictive battery health monitoring.

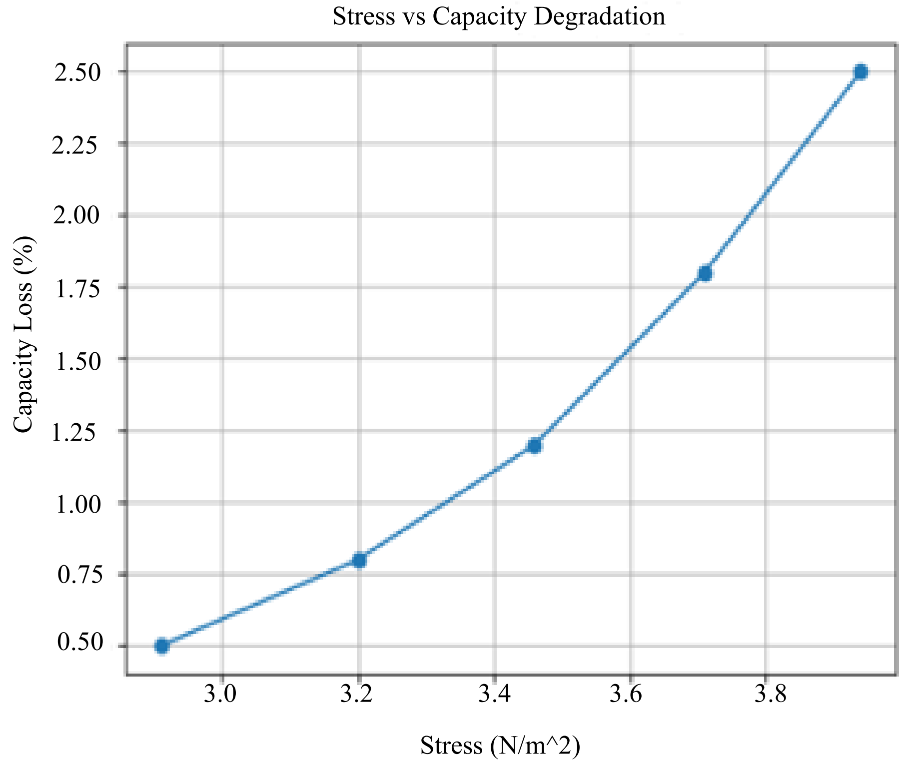

Figure 10. Stress vs. capacity degradation.

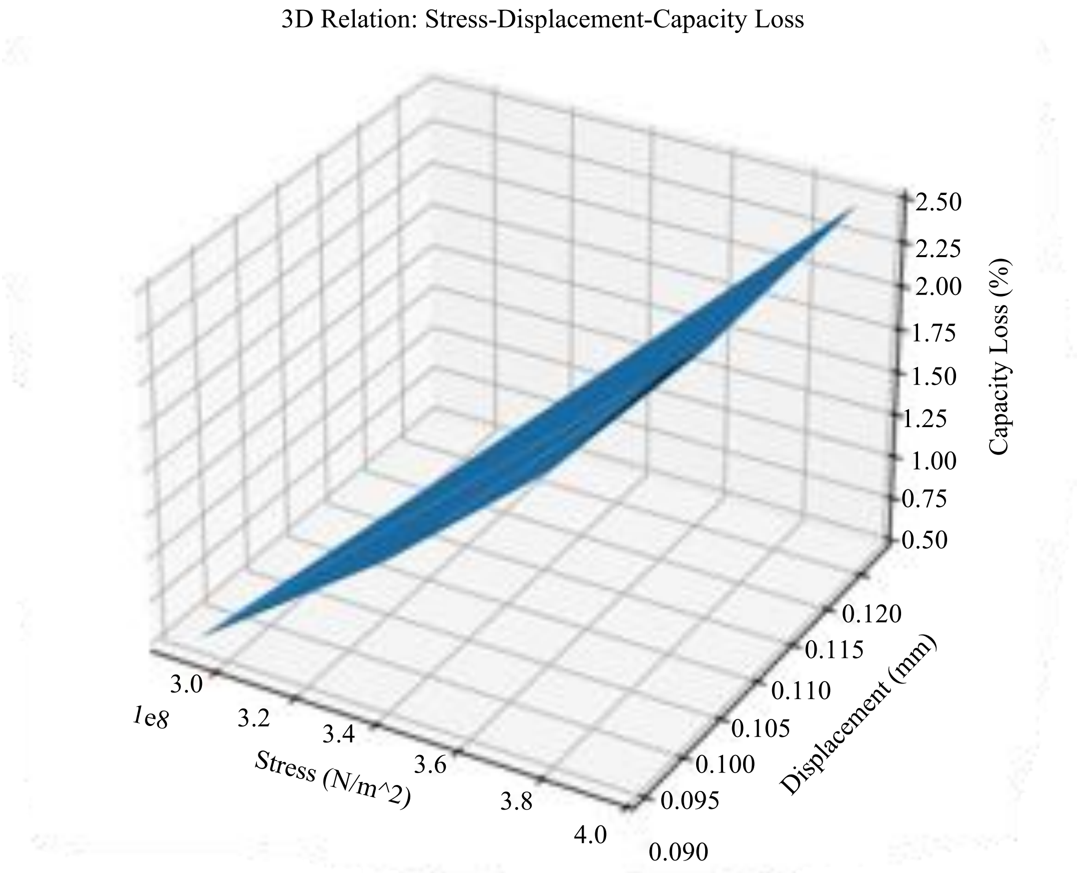

Figure 11. Stress displacement and capacity loss.

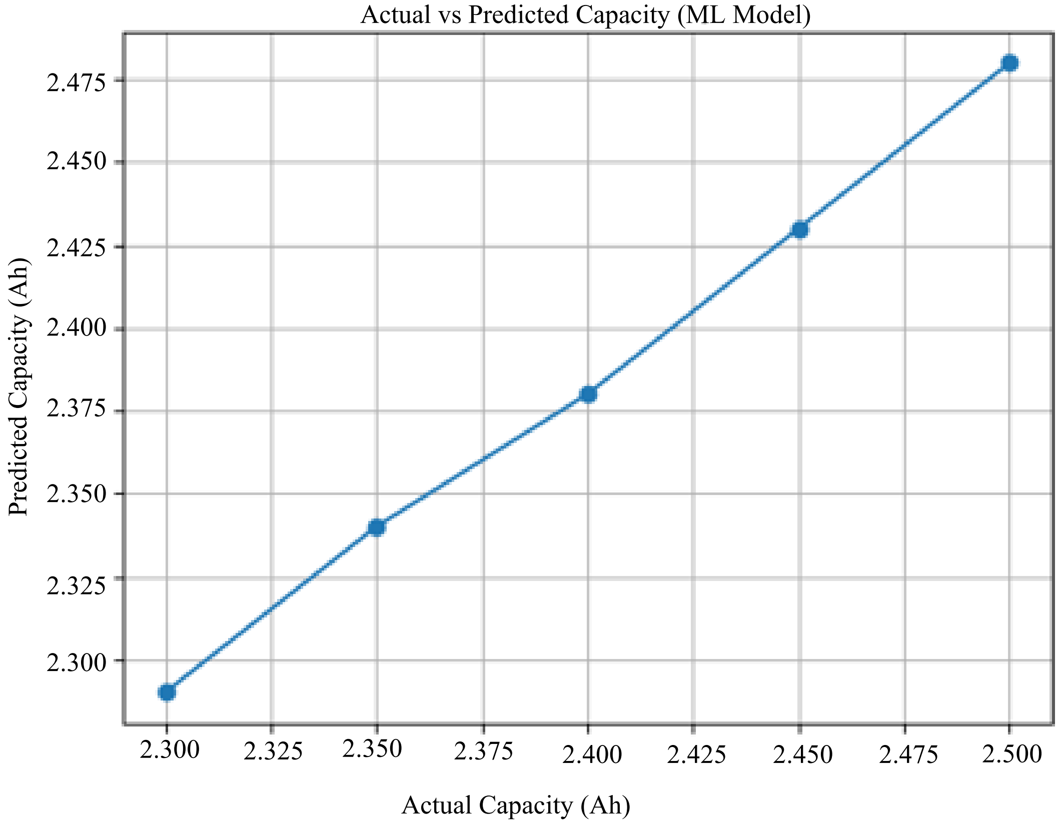

Figure 12. Actual vs. predicted capacity (ML model).

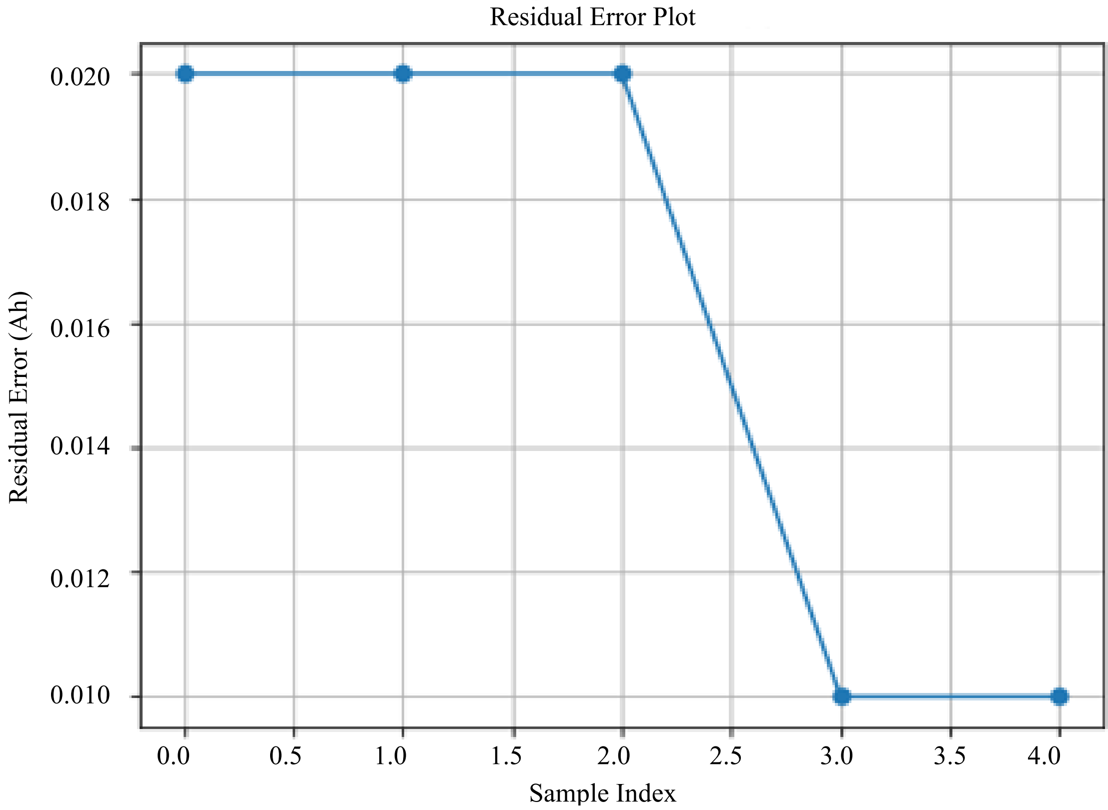

Figure 13. Residual error plot.

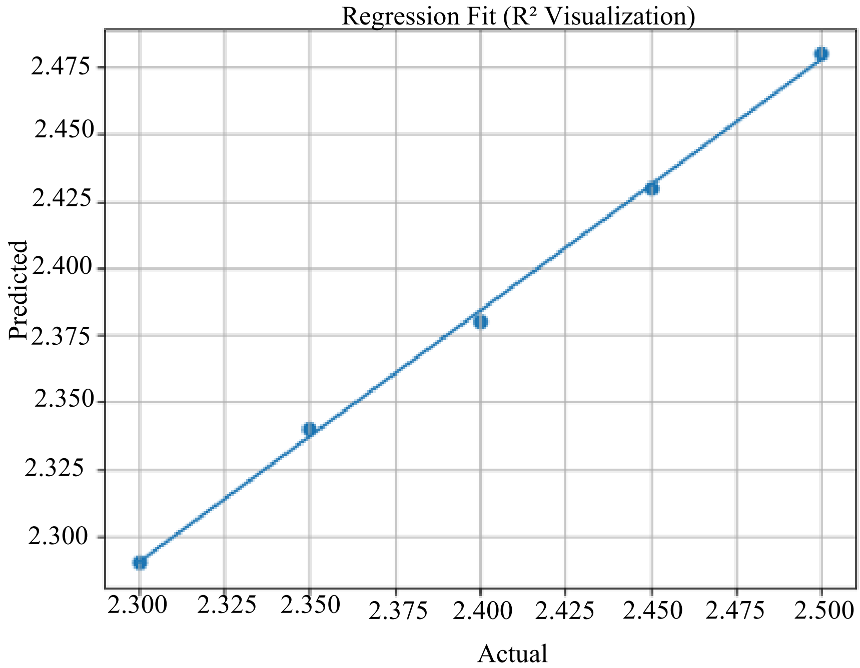

Figure 14. Regression fit (R^2 visualization).

Reliability and Safety Analysis

From the failure probability curve in Figure 15, it is confirmed that the probability of battery failure is exponentially related to stress. These observations are very useful for understanding battery failure. Moreover, even after structural failure and electrochemical degradation, no thermal runaway which aligns with controlled abuse testing observations reported in [1, 9] or explosion is observed in the experiments, confirming the reliability of the battery.

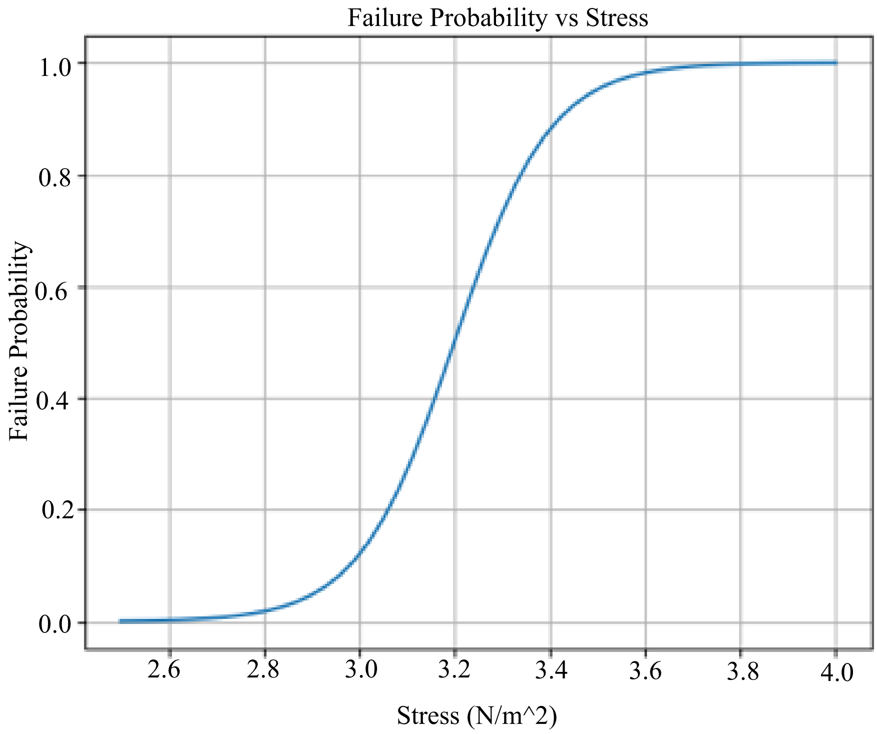

Figure 15. Failure probability vs. stress.

Comparison with Existing Techniques

Compared to traditional techniques, where only test data or simulations are considered, this proposed methodology considers all data sources. Moreover, this technique is more accurate than traditional techniques, and it can be utilized for real-time monitoring. Unlike previous works, where no direct correlation between mechanical and electrical parameters was established, this work clearly establishes a direct correlation between crash stress and battery degradation.

Interpretation of Results

From the above results, it can be concluded that mechanical abuse plays an important role in the degradation of lithium-ion batteries. The stress and deformation cause micro-cracks inside the battery, leading to instability in the battery voltage and an increase in battery resistance. The technique's accuracy is improved by enabling battery safety using machine learning approach.

The data within Table 4 are used to illustrate the effect of polymer composite protective structures on electro-mechanical characteristics of lithium-ion batteries when subjected to mechanical shock (crash) induced from high-speed impacts. Data comparing these characteristics of batteries protected using various types of composite protective materials (CFRP, GFRP, Kevlar/epoxy, shear thickening polymeric materials, PU foams, honeycomb polymeric composites) are presented and include measurements of stress, strain, displacement, and changes in capacity, voltage, and retained capacity. The comparison illustrates the capabilities of some composite materials to protect against physical damage; maintain structural integrity; and improve the reliability and safety of electrical power systems in vehicles due to impact forces.

Table 4. Comparative electro-mechanical performance of lithium-ion batteries with and without polymer composite protection.

Configuration	Peak stress	Maximum strain	Maximum displacement	Capacity fade	Voltage degradation	Capacity retention	Protection effect
No Protection	Highest	Highest	Highest	Severe	Significant	Lowest	Baseline.
CFRP Protection	Reduced	Reduced	Reduced	Low	Minor	High	Excellent stiffness and crash resistance.
GFRP Protection	Moderately Reduced	Reduced	Reduced	Moderate	Low	Moderate-High	Good impact protection.
Kevlar/Epoxy Composite	Significantly Reduced	Lowest	Lowest	Very Low	Minimal	Highest	Superior energy absorption.
Shear-Thickening Polymer	Reduced under high impact	Low	Low	Low	Minor	High	Adaptive impact mitigation.
PU Foam Protection	Moderate Reduction	Moderate	Moderate	Moderate	Moderate	Moderate	Shock and vibration damping.
Honeycomb Polymer Composite	Significantly Reduced	Low	Low	Low	Minor	High	High energy absorption capability.

PRACTICAL IMPLICATIONS FOR EV BATTERY PACK DESIGN

The conclusions from this research show that protective structures using polymer composite materials have potential for providing improved crashworthiness and greater safety with lithium-ion battery pack designs commonly found within electric vehicles. Kevlar/epoxy-laminated composites honeycombed composite structures, and shear-thickening polymer-based composites all function by absorbing impact energy due to the ability to deform or redistribute stress in an elastic/plastic manner. These effects will result in less mechanical damage to individual battery cells. All the composite materials investigated here possess the necessary properties (i.e., low weight, high impact strength, good durability, etc.) so as to be considered viable candidates for use as the housing structure for automotive battery packs. Additionally, the drop test and impact tests used here reflect typical mechanical abusive conditions (e.g., vehicle crashes, accidental drops) associated with electric vehicle battery operation and/or storage. Therefore, incorporation of these polymer composites in the enclosure for lithium-ion battery packs could potentially increase structural reliability, maintain capacity retention during cycling events, prevent further voltage degradation, and ultimately produce electric vehicle batteries that are safer/reliable.

Table 5 is a summary of expected improvements to be obtained with the use of various polymer composite protective materials to protect against extreme stresses at impact, retain battery capacity, absorb impact energy, and improve overall battery safety. Comparisons indicate that composites – such as Kevlar/epoxy laminates, shear-thickening polymeric materials, and honeycombs – will provide significantly better crash protection than other composites – such as CFRP or GFRP – by absorbing much greater amounts of energy and deforming under the same impact loads. Therefore, the data in this paper demonstrate the significant contributions made by polymer and composite materials to increase the crash-worthiness, durability and operational safety of lithium-ion batteries in electric vehicles.

Table 5. Performance improvement of polymer composite protective structures.

Material	Peak stress reduction (%)	Capacity retention (%)	Impact energy Absorption	Overall battery safety
No Protection	Base	Base	Low	Moderate
CFRP	20–35%	90–95%	High	High
GFRP	15–30%	88–93%	Moderate-High	High
Kevlar/Epoxy Composite	30–45%	92–97%	Very High	Very High
Shear-Thickening Polymer	25–40%	90–96%	Very High	Very High
PU Foam	10–20%	85–90%	Moderate	Moderate-High
Honeycomb Polymer Composite	25–40%	90–95%	High	High

CONCLUSION AND FUTURE SCOPE

Conclusions

The current study provided an experimental and theoretical investigation of mechanical shock damage from crashes to lithium-ion batteries and the effect of polymer composite protective systems on their electro-mechanical properties. Results indicated that increased drop heights and velocities cause significant increases in stress, strain, displacement, capacity loss, and voltage degradation in lithium-ion cells. These findings demonstrate how there is a large relationship between mechanical loading and the deteriorating electrical performance of these cells. Polymer composites (CFRP, GFRP, Kevlar/epoxy composites), shear thickening polymers, PU foam and honeycomb polymer composite materials showed good ability to mitigate impacts by absorbing impact energy and redistributing stresses along with controlling deformations. It was concluded that characterization techniques (SEM, FT-IR, XRD, DSC, TGA, impact tests, compressive tests) are needed to understand how composites behave and develop relationships between composite structural characteristics and properties. Additionally, it was shown that incorporating polymer nanocomposites, developing new surface engineering methods and using environmentally friendly composite technologies will improve the safety, thermal resistance, and longevity of lithium-ion batteries. Machine learning based predictive modeling showed potential for predicting lithium-ion battery state-of-health and degradation. In summary, this research provides a comprehensive methodological approach for relating design requirements for polymer composites, mechanical responses to abuse and electrochemical performance; providing a basis for designing lighter weight and higher performing lithium-ion batteries for use in EV applications.

Future Scope

In order to advance in developing the next generation of polymer composite structures that provide multiple functions (i.e., load-carrying capacity, heat transfer, energy absorption, and electrical energy storage) researchers will need to develop a variety of new polymer nanocomposite materials that include graphene, carbon nanotubes (CNTs), MXenes, nanoclays, etc. These types of nanomaterials may enhance both the electrochemical stability and crash worthiness of polymer composite batteries. Researchers are exploring ways to integrate self-healing polymers, smart interfaces, functional coatings and bio inspired polymer composite designs into polymer composite batteries as a means of increasing their reliability and longevity. Artificial intelligence/machine learning/digital twin technology is being researched as a way to streamline the process of selecting suitable materials; optimizing the design of polymer composite battery components; and monitoring the performance of polymer composite batteries in real time. Future experiments should test various configurations of battery cells including pouch cell configurations, prismatic cell configurations and full battery pack configurations subjected to multiaxial impacts and coupled thermo-mechanical loads. In addition to advancing the state-of-the-art in terms of material science and mechanical properties, researchers should explore environmentally friendly approaches – such as using recyclable thermoplastics, using biodegradable polymers, utilizing natural fiber composites, implementing circular economy principles, and performing life cycle assessments – to ensure the sustainability of polymer composite battery protective systems.

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REFERENCES

1. Nair SA, Wu XY, Das PK, Fowler M. A review of nail penetration and thermal abuse tests of lithium-ion batteries and their emission characterization. Batteries (Basel). 2026;12(2):74.
2. Sheikh MS. Thermal and electrical failure analysis of lithium-ion battery after crash [thesis]. 2017.
3. Dabasa T, Lemu HG, Regassa Y. A review on the crashworthiness of bio-inspired cellular structures for electric vehicle battery pack protection. Computation. 2025;13(9):217.
4. Dong C, Yang H, Yang Z, Cao W, Miao Z, Ren L, et al. Protective performance of shear thickening gel modified epoxy sealant on lithium-ion batteries under mechanical abuse. Energy. 2024;296:131152.
5. Ma Y, He H, Wang N, Tang H, Xia H, Chen G, et al. Crash failure prediction of lithium-ion batteries based on finite element and machine learning methods. Lat Am J Solids Struct. 2026;23(3):e8785.
6. Zhu X, Wang H, Allu S, Gao Y, Cakmak E, Hopkins EJ, et al. Investigation on capacity loss mechanisms of lithium-ion pouch cells under mechanical indentation conditions. J Power Sources. 2020;465:228314.
7. Marcicki J, Bartlett A, Yang XG, Mejia V, Zhu M, Chen Y, et al. Battery abuse case study analysis using LS-DYNA. In: Proceedings of the 14th International LS-DYNA Users Conference; 2016 Jun.
8. L'Eplattenier P, Caldichoury I, Marcicki J, Bartlett A, Yang XG, Mejia V, et al. A distributed Randle circuit model for battery abuse simulations using LS-DYNA. In: Proceedings of the 14th International LS-DYNA Users Conference; 2016 Jun.
9. Mustaffa Z, Budiman BA. External impacts and assessment of electric vehicles: Probabilistic risk assessment framework. In: 2025 8th International Conference on Electric Vehicular Technology (ICEVT); 2025 Aug. p. 1–6.

10. Zhang C, Santhanagopalan S, Pesaran A, Sahraei E, Wierzbicki T. Coupling of mechanical behavior of lithium-ion cells to electrochemical-thermal models for battery crush. Golden (CO): National Renewable Energy Laboratory; 2015.
11. Wierzbicki T, Sahraei E, Dajka S, Li G, Santhanagopalan S, Zhang C, et al. Coupling mechanical with electrochemical-thermal models for batteries under abuse. Golden (CO): National Renewable Energy Laboratory; 2015. Report No.: NREL/PR-5400-64148.
12. Hu R, Zhou D, Jia Y, Chen Y, Zhang C. Dynamic mechanical behaviors of load-bearing battery structure upon low-velocity impact loading in electric vehicles. eTransportation. 2024;21:100334.
13. Kang HC, You YS, Lee GG. Cooling water injection for EV battery fires: A targeted method to suppress thermal runaway. Fire Saf J. 2025;104503.
14. Farzaneh F. Development of a multifunctional lithium-ion battery module for electric vehicles [dissertation]. Tallahassee (FL): Florida State University; 2025.
15. Shao Y. Current research progress and future perspectives of early fire prediction modeling for electric vehicles. SAE Int J Electr Veh. 2025;15(1):1–16.
16. Bubanja M, Pajić N, Aleksandrović B, Vukicević AM, Djapan M. Electrical hazards in electric vehicles: Risks and safety measures. 2025.
17. Zhang D, Sun Z, Zhang H, Liao J. Manufacturability-constrained multi-objective optimization of an EV battery pack enclosure for side-pole impact. World Electr Veh J. 2025;16(11):632.
18. Pesaran A, Ban C, Cao L, Graf P, Keyser M, Kim GH, et al. Energy storage annual progress report for FY15. Golden (CO): National Renewable Energy Laboratory; 2016. Report No.: NREL/MP-5400–65317.
19. Lian F, Wang D, Zhang X, Meng Z, Xu W. Hybrid cellular automata based multi-case topology optimization method for battery pack system structure design in CTB automotive. Proc Inst Mech Eng Part D J Automob Eng. 2025;239:09544070251395187.
20. Brewer J, Nasser A, Van Eikema Hommes Q, Najm W, Becker C. Safety management of automotive rechargeable energy storage systems: The application of functional safety principles to generic rechargeable energy storage systems. 2018.
21. Ayrilmis N, Kanat G, Yildiz Avsar E, Palanisamy S, Ashori A. Utilizing waste manhole covers and fibreboard as reinforcing fillers for thermoplastic composites. J Reinf Plast Compos. 2025;44(17–18):1108–1118.
22. Almeshaal M, Palanisamy S, Murugesan TM, Palaniappan M, Santulli C. Physico-chemical characterization of Grewia monticola Sond fibers for prospective application in biocomposites. J Nat Fibers. 2022;19(17):15276–15290.
23. Palanisamy S, Mayandi K, Palaniappan M, Alavudeen A, Rajini N, Vannucchi de Camargo F, et al. Mechanical properties of Phormium tenax reinforced natural rubber composites. Fibers. 2021;9(2):11.
24. Ramasubbu R, Kayambu A, Palanisamy S, Ayrilmis N. Mechanical properties of epoxy composites reinforced with Areca catechu fibers containing silicon carbide. BioResources. 2024;19(2):2353–2370.
25. Palanisamy S, Mayandi K, Dharmalingam S, Rajini N, Santulli C, Mohammad F, et al. Tensile properties and fracture morphology of Acacia caesia bark fibers treated with different alkali concentrations. J Nat Fibers. 2022;19(15):11258–11269.
26. Flamberg S, Rose S, Stephens D. Analysis of published hydrogen vehicle safety research. 2010.
27. Xu P, Li J, Lei N, Zhou F, Sun C. An experimental study on the mechanical characteristics of Li-ion battery during overcharge-induced thermal runaway. Int J Energy Res. 2021;45:1–13.
28. Allen J. Review of polymers in the prevention of thermal runaway in lithium-ion batteries. Energy Rep. 2020;6:217–224.
29. Kaliaperumal M, Dharanendrakumar MS, Prasanna S, Abhishek KV, Chidambaram RK, Adams S, et al. Cause and mitigation of lithium-ion battery failure: A review. Materials (Basel). 2021;14(19):5676.
30. Zhou H, He J, Gao S, Cao X, Li C, Zhang Q, et al. Critical perspectives on the design of polymeric materials for mitigating thermal runaway in lithium-ion batteries. Polymers (Basel). 2025;17(9):1227.

31. Gao Y, Hao Z, Jiang Y, Yao T, Wang L. Mechanical degradation on defective lithium-ion batteries. J Electrochem Energy Convers Storage. 2025;22(2):020905.
32. Kawsar I, Li H, Liu B, Zhang Y, Pan Y. Enhancing mechanical reliability and safety performance of a battery pack system for electric vehicles: A review. eTransportation. 2025;26:100469.
33. Chen M, Zhu M, Zhang S, Ouyang D, Weng J, Wei R, et al. Experimental investigation on mitigation of thermal runaway propagation of lithium-ion battery module with flame retardant phase change materials. Appl Therm Eng. 2023;235:121401.
34. Tian X, Yi Y, Fang B, Yang P, Wang T, Liu P, et al. Design strategies of safe electrolytes for preventing thermal runaway in lithium-ion batteries. Chem Mater. 2020;32(23):9821–9848.
35. Zhao H, Bo X, Zhang Z, Wang L, Daoud WA, He X. Insight into puncture-induced thermal runaway in lithium-ion batteries to reduce fire risks in electric vehicle collisions. Battery Energy. 2025;4(6):e70041.

