"Next-Gen Battery Cooling: Using AI, New Tech, and Sustainability for Electric Vehicles"

Karan M. Gandhi [a,*], **Deep T. Khalasi** [b]

[a] *Department of Automobile Engineering, GIDC Degree Engineering College, Abrama, Navsari, India*

[b] *Department of Mechanical Engineering, Government Engineering College, Bharuch, India*

ARTICLE INFO

Keywords:
AI-Driven Thermal Management
Electric Vehicle (EV) Batteries
Phase-Change Materials (PCMs)
Predictive Battery Management
Sustainable Cooling Systems
Battery Thermal Management Systems (BTMS)

ABSTRACT

As electric vehicles (EVs) continue to advance, the demand for efficient, safe, and sustainable battery thermal management systems (BTMS) has become increasingly critical. This review paper explores the integration of artificial intelligence (AI), cutting-edge technologies, and sustainable practices in next-generation battery cooling systems. It examines AI-driven models for predicting battery states, thermal behavior, and failure conditions, while assessing the benefits and limitations of these approaches. The paper also highlights innovative technologies such as additive manufacturing for customized cooling structures, bioinspired designs for enhanced thermal performance, and smart materials adaptable to varying environmental conditions. Additionally, it investigates advanced cooling methods like mist-based systems for thermal runaway prevention and hybrid cooling strategies that combine air, liquid, and phase change materials (PCM). A strong emphasis is placed on sustainability, addressing the environmental, economic, and social impacts of BTMS innovations. By leveraging AI, advanced materials, and green engineering practices, this review aims to provide a roadmap for developing next-gen BTMS that optimize performance, extend battery life, and mitigate safety risks in EVs. The paper concludes with future research directions, emphasizing the need for continuous innovation to meet the evolving demands of electric mobility and contribute to a more sustainable future.

1. Introduction

The adoption of electric vehicles (EVs) has surged as part of the global effort to reduce greenhouse gas emissions, improve air quality, and combat climate change. Central to the transition from internal combustion engine vehicles to EVs is the lithium-ion battery (LiB), which serves as the primary energy storage system for these vehicles. However, while LiBs offer high energy density, long cycle life, and relatively low self-discharge rates, their performance is significantly influenced by temperature. Lithium-ion batteries generate substantial amounts of heat during charge-discharge cycles, and if this heat is not effectively managed, it can lead to a number of undesirable outcomes, including battery degradation, thermal runaway, reduced efficiency, and even catastrophic failures such as fires or explosions [1,2]. Consequently, efficient thermal management has become a critical component in the design and operation of EVs, ensuring that LiBs perform optimally throughout their operational lifespan.

Battery Thermal Management Systems (BTMS) play a pivotal role in maintaining safe and optimal operating temperatures within lithium-ion batteries. Without effective thermal regulation, battery performance degrades significantly, potentially leading to shortened lifespan, lower capacity, and safety concerns. Traditional BTMS technologies, such as air cooling, liquid cooling, and heat pipes, have been widely studied and deployed in the past two decades to mitigate thermal effects [3, 4]. However, while these approaches can maintain battery temperature within safe ranges, they face challenges related to energy efficiency, scalability, and adaptability to the dynamic operating conditions typical of modern EVs [5]. As a result, there is a growing need for more efficient, adaptable, and sustainable thermal management solutions to address these challenges.

Recent advancements in Artificial Intelligence (AI), machine learning (ML), and deep learning (DL) offer significant promise in overcoming these limitations. AI technologies allow for predictive thermal management by enabling real-time monitoring of battery temperature, state-of-charge (SOC), state-of-health (SOH), and other critical parameters. These technologies can also optimize the operation of thermal management systems by predicting temperature variations and adjusting cooling strategies dynamically based on real-time data [6, 7]. AI-driven systems have the potential to not only enhance thermal efficiency but also improve battery safety by identifying potential

failure modes, such as thermal runaway, before they manifest. Several studies have demonstrated the potential of AI in optimizing the performance of BTMS, yet integrating AI into BTMS remains an area of ongoing research and development [8, 9].

A particularly promising area of development involves the integration of phase-change materials (PCMs) into BTMS. PCMs are materials that can absorb or release large amounts of latent heat during phase transitions, thereby helping to maintain stable temperatures within a system. This ability makes PCMs highly suited for use in thermal management applications, as they can effectively stabilize the battery's temperature under varying charge and discharge conditions [10]. When combined with AI-driven predictive models, the potential for optimizing thermal performance increases substantially. AI can predict temperature fluctuations, optimize PCM placement and configuration, and adjust cooling strategies accordingly. This combination of PCMs and AI offers an exciting new direction in BTMS research, but it is an area that remains underexplored and requires further investigation [11, 12].

Moreover, sustainability is becoming an increasingly important consideration in the design of BTMS. As the adoption of EVs grows, the demand for efficient and environmentally friendly cooling solutions becomes more pressing. Traditional cooling systems consume a significant amount of energy, contributing to the overall energy consumption of EVs and potentially reducing the vehicle's range. One potential solution is the integration of renewable energy sources, such as solar or wind power, to operate the cooling systems. Renewable energy-powered BTMS can reduce the environmental footprint of EVs by providing a sustainable, self-sustaining solution to thermal management. Additionally, coupling renewable energy sources with AI-driven predictive models creates a system that can dynamically optimize the cooling process based on real-time conditions and energy availability, further enhancing both energy efficiency and sustainability [13, 14]. Such systems align with global efforts to achieve the United Nations Sustainable Development Goals (SDGs), particularly those related to climate action and clean energy [15, 16].

A variety of studies have highlighted the potential for integrating renewable energy sources with battery thermal management. For instance, research has explored the use of solar energy to power the thermal management systems in both EVs and stationary energy storage systems [17]. Additionally, advancements in energy storage technologies, such as the use of hybrid storage systems (combining lithium-ion batteries with other storage technologies), have opened the door to more sustainable solutions for BTMS. These hybrid systems, which combine renewable energy sources with thermal management, could significantly reduce the dependence on grid power and reduce the overall carbon footprint of EVs [18, 19]. Furthermore, the integration of renewable energy sources into BTMS aligns with ongoing efforts to make EVs and energy storage systems more environmentally friendly and energy-efficient.

As the EV market continues to expand, it is essential to explore and develop new materials, technologies, and approaches that can enhance the thermal management of lithium-ion batteries. Innovations such as AI-assisted thermal optimization, renewable energy-powered cooling, and advanced materials like PCMs offer promising solutions that can significantly improve the efficiency and safety of EVs. However, numerous challenges remain in integrating these technologies into practical, large-scale applications. For example, AI models require large datasets for training and validation, and ensuring real-time implementation of these models remains a significant hurdle. Furthermore, the scalability of PCM-based systems and the effective integration of renewable energy sources into BTMS are areas that require further research [20].

This review paper provides a comprehensive analysis of the latest advancements in AI-driven predictive thermal management for lithium-ion batteries in EVs, with a focus on the integration of phase-change materials and renewable energy-powered cooling systems. Section 2 discusses the fundamental principles of thermal management in LiBs, along with the challenges associated with traditional BTMS approaches. Section 3 delves into the role of AI, machine learning, and deep learning in optimizing thermal management, emphasizing the potential of predictive models and real-time data analytics. Section 4 examines recent advancements in PCMs and their integration with AI-driven systems, highlighting their benefits for maintaining safe operating temperatures. Section 5 explores the potential of renewable energy-powered cooling systems and their synergy with AI-based predictive models, outlining the sustainability benefits they offer. Finally, Section 6 identifies the challenges and future research directions in this

field, focusing on the need for interdisciplinary collaboration and innovation to achieve efficient, safe, and sustainable BTMS solutions.

Nomenclature

BTMS	Battery Thermal Management System	SOC	State of Charge
EV	Electric Vehicle	SOH	State of Health
PCM	Phase Change Material	LIB	Lithium-Ion Battery
AI	Artificial Intelligence	CFD	Computational Fluid Dynamics
ML	Machine Learning	TR	Thermal Runaway
DL	Deep Learning	TES	Thermal Energy Storage
PINN	Physics-Informed Neural Network	SMA	Shape Memory Alloy
SVM	Support Vector Machine	MOF	Metal-Organic Framework
DRL	Deep Reinforcement Learning		
ANN	Artificial Neural Network		
CNN	Convolutional Neural Network,		
NSGA-II	Nondominated Sorting Genetic Algorithm-II		
PSO	Particle Swarm Optimization		
MOGA	Multi-Objective Genetic Algorithm		
WPM	Weighted Product Method		
COSMOS	Concurrent Surrogate Selection		
RSM	Response Surface Methodology		
TO	Topology Optimization		
TPMS	Triply Periodic Minimal Surface		
NEPCM	Nanoparticle-Enhanced Phase Change Material		

2. **Current State of Battery Cooling Technologies.**

Battery thermal management systems (BTMS) are critical for ensuring the safety, performance, and longevity of electric vehicle (EV) batteries. This section provides an overview of traditional cooling methods, their pros and cons, and key limitations.

2.1 Traditional Cooling Methods

2.1.1 Air Cooling

How It Works: Air cooling uses natural or forced convection to dissipate heat from the battery pack. Fans or blowers are often employed to enhance airflow.

Applications: Commonly used in early-generation EVs like the Nissan Leaf due to its simplicity and low cost.

Example: The Nissan Leaf employs a passive air-cooling system, which relies on ambient air to regulate battery temperature.[26]

2.1.2 Liquid Cooling

How It Works: Heat pipes transfer heat from the battery to a heat sink using a working fluid that evaporates and condenses.

Applications: Widely used in high-performance EVs like Tesla Model S and BMW i3 [24], [25].

Example: Tesla's liquid cooling system integrates coolant loops within the battery pack, ensuring uniform temperature distribution [24].

2.1.3 Phase-Change Materials (PCM)

How It Works: PCM absorbs heat during phase transitions (solid to liquid) to maintain battery temperature within a safe range.[32]

Applications: Emerging in EVs for its passive cooling capabilities and energy efficiency.

Example: Research by Al-Hallaj and Selman (2000) demonstrated the use of paraffin-based PCM for Li-ion battery cooling.[21]

2.1.4 Heat Pipes

How It Works: Heat pipes transfer heat from the battery to a heat sink using a working fluid that evaporates and condenses.

Applications: Suitable for compact EV designs due to their high thermal conductivity.

Example: Studies have shown heat pipes can reduce battery temperature by up to 10°C in high-load conditions.[27]

2.2 Pros and Cons of Traditional Cooling Methods

Traditional cooling methods for EV batteries include **air cooling**, **liquid cooling**, **phase-change materials (PCM)**, and **heat pipes**. Each method has unique advantages and drawbacks:

Table 1

Comparative Table: Pros and Cons of Traditional Cooling Methods

Cooling Method	Pros	Cons
Air Cooling	Low cost, simple design, lightweight, reliable	Low efficiency, poor performance in high-temperature environments
Liquid Cooling	High efficiency, uniform temperature distribution, scalable	Complex design, higher cost, risk of leakage
PCM	Passive operation, energy-efficient, compact, silent	Limited heat absorption capacity, high material cost
Heat Pipes	High thermal conductivity, compact, no moving parts, silent	Limited scalability, high cost for large battery packs

2.3 Limitations of Traditional Cooling Methods

1.Energy Consumption:

Liquid cooling systems require additional energy to pump coolant, reducing overall EV efficiency.

Example: A study by Rao et al. (2018) found that liquid cooling systems consume up to 5% of the battery's energy. [22]

2.Thermal Runaway Risks:

Inadequate cooling can lead to thermal runaway, a dangerous condition where battery temperatures escalate uncontrollably.

Example: The Chevy Bolt recall (2021) highlighted the risks of insufficient cooling in Li-ion batteries. [29]

3.Environmental Concerns:

Traditional coolants (e.g., glycol-based liquids) are toxic and non-biodegradable.

Example: Disposal of liquid coolants poses environmental hazards, as highlighted by Zhang et al. (2020). [23]

4.Scalability Issues:

Air cooling struggles to meet the demands of larger battery packs in modern EVs. [26]

Example: High-performance EVs like the Tesla Model S have shifted to liquid cooling due to air cooling's limitations. [24]

Figure 1: Comparison of Cooling Methods in EVs.

Cooling Method	Efficiency	Cost	Scalability
Air Cooling	Moderate: Adequate for low to medium heat.	Low: Affordable and easy to maintain.	High: Simple to scale for most systems.
Liquid Cooling	High: Excellent heat transfer capability.	Moderate to High: Equipment and maintenance costs.	Moderate: More complex but possible with planning.
PCM Cooling	High: Absorbs and stores heat effectively.	Moderate: Depends on material choice.	Limited: Thermal recharge constraints.
Heat Pipe Cooling	Very High: Extremely efficient for localized cooling.	Moderate: Design complexity affects costs.	Moderate: Scales well for specific setups but less suited for large systems.

3. Role of AI in Battery Thermal Management System.

Artificial Intelligence (AI) is revolutionizing Battery Thermal Management Systems (BTMS) by enabling smarter, more efficient, and adaptive cooling strategies. AI-driven approaches, such as machine learning and neural networks, are used to predict battery temperature trends, optimize cooling performance, and prevent thermal runaway.

3.1 AI-Driven Predictive and Optimization Strategies for Battery Thermal Management Systems (BTMS)

Artificial intelligence (AI) has emerged as a critical component across various engineering disciplines [34–36], particularly in the realms of electric vehicles [37,38] and energy storage systems [39]. While AI's capabilities in prediction, classification, and recognition have been extensively applied in studies related to Battery Thermal Management Systems (BTMS) [40], there remains a need for more reliable predictive methodologies in this domain [41]. AI-based models have frequently been employed as surrogate models [42,43], often integrated with Computational Fluid Dynamics (CFD) to optimize diverse BTMS configurations [44,45]. Safety, a crucial parameter, has also been explored using AI techniques [46]. The majority of AI applications in BTMS focus on enhancing system control [47].

Physics-informed neural networks have demonstrated the ability to predict the thermal behavior of batteries and BTMS [48,49]. AI can also forecast battery surface temperatures or maximum temperature differentials [50,51]. By estimating the State of Temperature (SOT) through AI, more efficient BTMS designs can be developed [52]. Additionally, AI can predict battery heat generation [53], as well as other BTMS parameters such as entropy generation [54] and Nusselt numbers [44]. Various AI techniques, including deep learning [55], gradient-based ensemble machine learning [54], feed-forward networks [44], Extreme Learning Machine (ELM) [56,57], linear regression, k-nearest neighbors, random forests, decision trees, and Digital Twin models [40], have been applied to BTMS.

AI and Machine Learning (ML) models serve as surrogate models for BTMS optimization, often combined with numerical models like CFD to predict and simulate system behavior. Duraisamy and Kaliyaperumal evaluated three ML models for optimizing cell balancing in battery packs [58]. Chen et al. utilized a Support Vector Machine (SVM) to

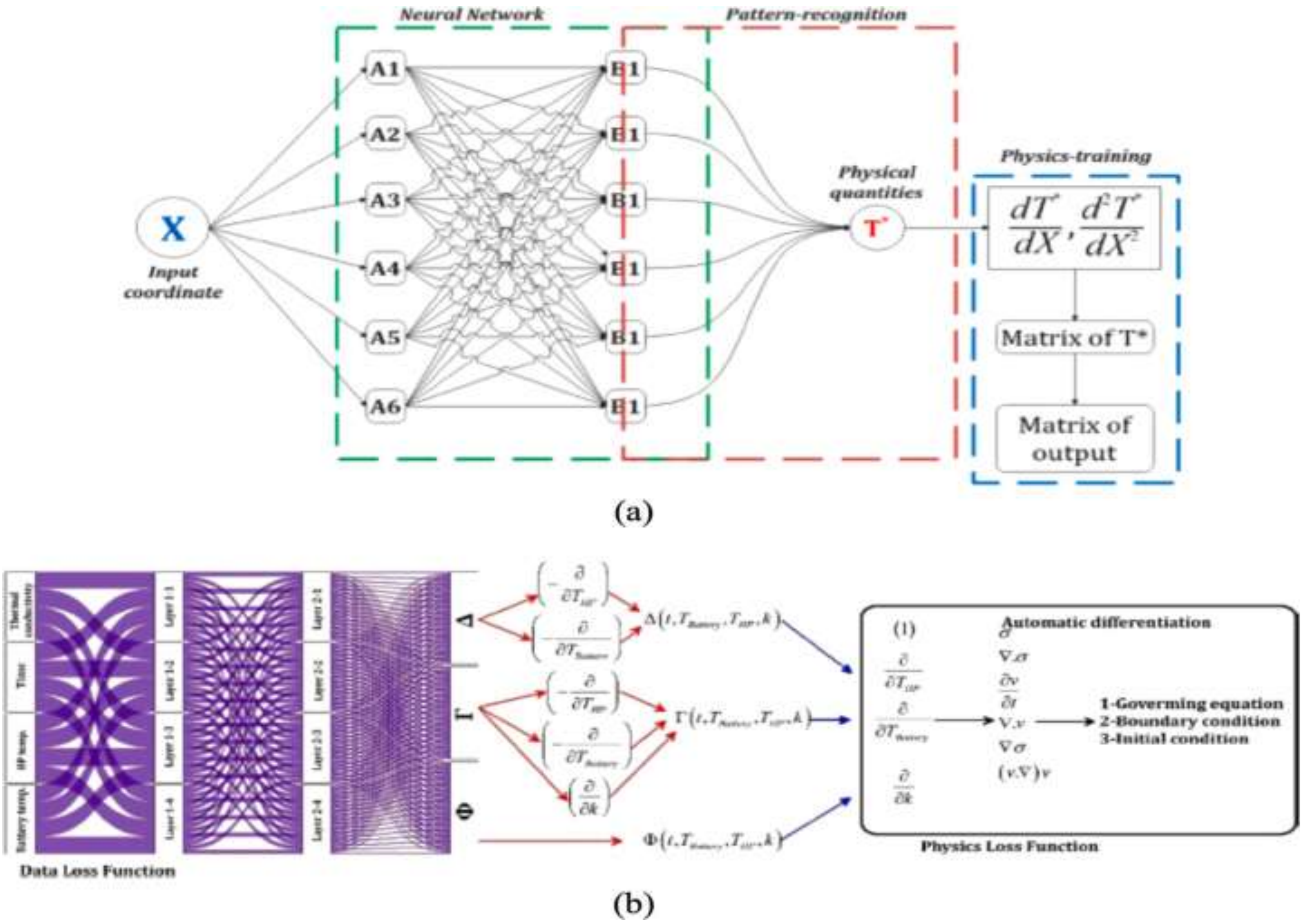


Figure 2: Neural network models incorporating physical principles for predicting battery thermal behavior.

predict thermal behavior and pressure in a cold plate BTMS, subsequently optimizing the system using a nondominated sorting genetic algorithm (NSGA-II) [59]. Similarly, Su et al. employed a Multilayer Perceptron Artificial Neural Network (MLP ANN) to optimize a U-shaped cooling channel BTMS, achieving an R^2 value of 0.9942 for temperature and flow pressure predictions [45].

Physics-informed neural networks (PBNN) have significantly impated the simulation, modeling, and prediction of thermal behavior in various systems [60]. These networks leverage experimental data to formulate Navier–Stokes equations, enabling accurate predictions of flow behavior and properties. Mesgarpour et al. [48] used a Physics-Informed Artificial Neural Network (PBANN) to predict battery thermal behavior under different cooling conditions, achieving a 65.41% reduction in computation time compared to CFD methods, with 99.87% prediction accuracy. Another study combined physics-informed machine learning with visual tracking to create a Pattern-Based Machine Learning (PBML) model, which effectively predicted battery temperature in heat pipe BTMS, reducing prediction complexity and time [49].

Selecting the optimal ML method for predicting battery thermal behavior remains challenging [61]. One study compared six ML methods and found regression trees to be the most effective for predicting maximum battery temperature, with sensitivity analysis further improving model performance [62]. AI and ML methods have also been used to predict battery states (charge and temperature). For instance, Electrochemical-Thermal-Neural Networks (ETNN) have predicted heat generation and temperature states in Li-ion batteries [52], while simpler MLP ANNs have also been employed for heat generation prediction [53]. These models offer faster computation and greater simplicity compared to traditional electrochemical-thermal models [63].

Deep learning models, such as Long Short-Term Memory (LSTM), have proven effective in predicting battery thermal behavior over time, with low dependency on physical models [51]. Fully Connected Deep Network Models (DNN) have also been used to predict maximum temperatures and temperature differences in Li-ion batteries, optimizing BTMS structures and operating parameters [55]. Phase Change Materials (PCM) are often used in hybrid BTMS to enhance performance, with AI models like Gradient Boosting Decision Trees (GBDT) predicting PCM properties such as liquid fraction and entropy generation [54]. ANN models have also been developed to predict thermal behavior in hybrid BTMS, achieving less than 3.5% error in temperature predictions [43].

Material selection, particularly for liquid-based BTMS, is another critical challenge. AI can streamline the evaluation of different coolants, such as water, nanofluids, and oils. Mokashi et al. developed an ANN model to predict Nusselt numbers for various coolants, demonstrating the robustness of MLP ANN for such predictions [44]. ML models have also been applied to predict thermal behavior under failure

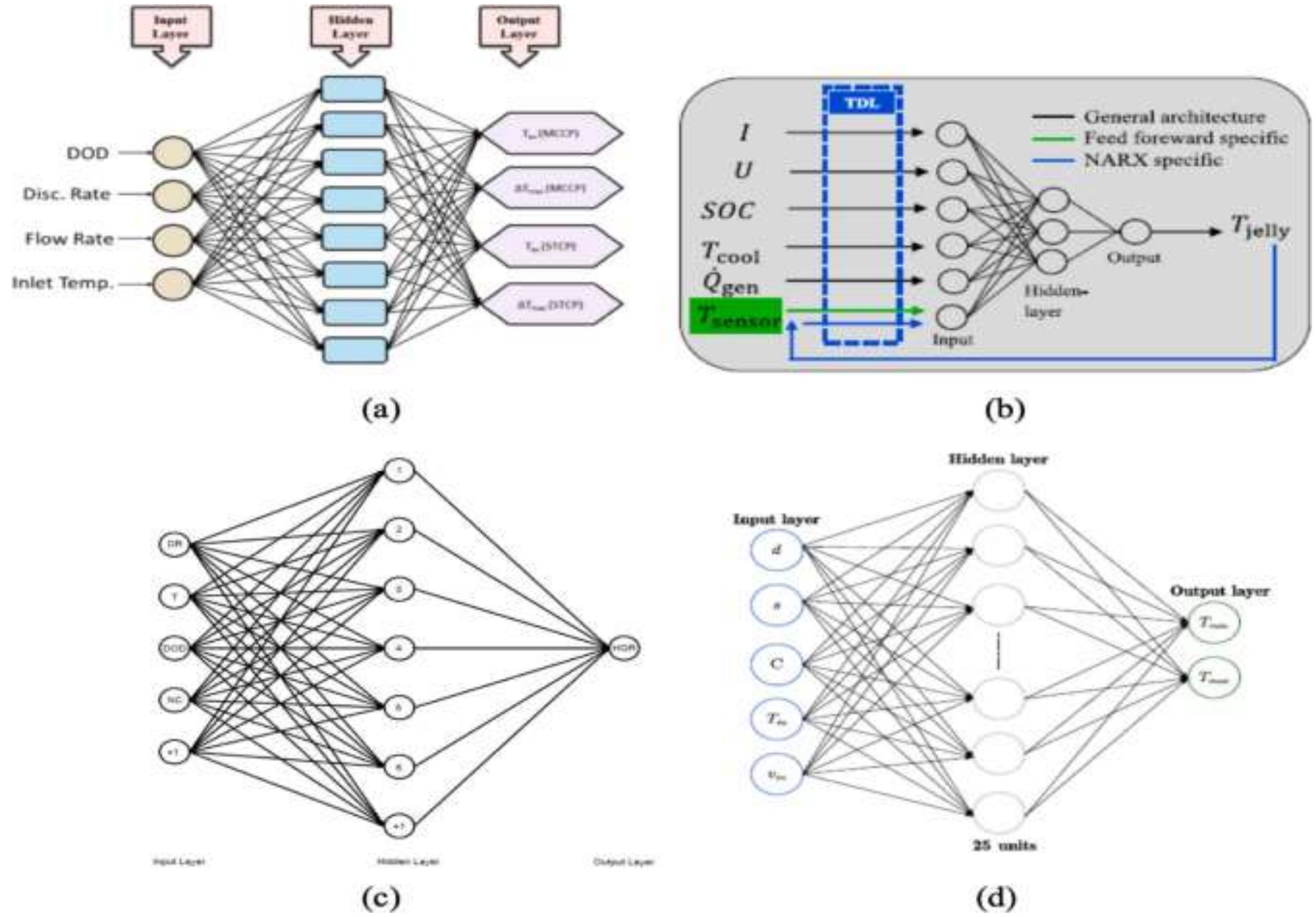


Figure 3: ANN Models for Forecasting Battery Thermal Performance

conditions, such as external short circuits, with Extreme Learning Machine (ELM) models outperforming traditional thermal models in both accuracy and computation time [56].

Comparative studies of ML models have highlighted the superior performance of decision tree models in predicting BTMS thermal behavior, particularly for complex problems [65]. Experimental validation of AI models in BTMS has shown promising results, with ANN and Elman-NN models accurately predicting thermal characteristics in battery packs under varying conditions [66]. Other studies have demonstrated the high accuracy of ANN models in predicting battery module temperatures, with regression coefficients (R^2) as high as 0.99998 [67]. Real-world data collection from electric vehicles, such as the MG ZS EV, has further validated the effectiveness of MLP models in forecasting battery health factors [68].

Experimental setups are essential for validating AI models. For example, Convolutional Neural Networks (CNNs) have been used to predict the internal temperature of lithium-ion battery packs, achieving a mean squared error (MSE) of 0.047 [71]. Combining AI with advanced cooling technologies has been shown to reduce battery temperatures by over 25% [70], underscoring the transformative potential of AI in BTMS optimization and design.

3.2 Strengths and Weaknesses of AI Technology and Methods.

Artificial intelligence (AI) technologies and methodologies exhibit distinct strengths and weaknesses, making them suitable for specific applications in battery thermal management systems (BTMS) and related fields. For example, artificial neural networks (ANNs) are widely utilized for predicting battery temperature, state of charge (SOC), and state of health (SOH), as well as optimizing cooling systems [85,86]. ANNs have demonstrated high accuracy in temperature prediction ($R^2 = 0.99$) [64] and have proven effective in enhancing cooling efficiency and reducing energy consumption [86]. However, their reliance on large datasets for training and validation poses a significant limitation [64].

Machine learning (ML) techniques are primarily employed to optimize BTMS design and operations, improving thermal performance and safety, particularly in fast charge/discharge scenarios [87]. ML methods have also been successful in reducing system weight and enhancing cooling efficiency [88,89]. Despite these advantages, the development and integration of ML models are often complex and resource-intensive.

Deep learning (DL) and deep reinforcement learning (DRL) offer the ability to explore multiple optimal solutions for battery thermal arrangements and cooling strategies [83]. However, these methods come with high computational costs, implementation complexity, and a need for significant expertise to fine-tune models. Additionally, they are prone to overfitting, which can compromise their generalization capabilities [90].

Support vector machines (SVM) and fuzzy logic are also employed in battery-related applications, such as estimating SOH and predicting other critical parameters. Hybrid algorithms, like genetic algorithm-particle swarm optimization (GA-PSO) combined with fuzzy logic, have shown promise in solving complex engineering problems by balancing thermal management with practical design parameters [91]. For instance, fuzzy logic-based controllers have outperformed traditional PID systems in managing lithium-ion battery thermal performance, achieving better temperature regulation, efficiency, and longevity [92]. In one study, a fuzzy logic-based system reduced battery consumption by 10% compared to PID control [93].

Gaussian process (GP) models have been effective in multi-objective optimization, particularly for energy efficiency in BTMS. These models have demonstrated significant improvements, such as a 26.67% reduction in cooling water velocity and a 24.18% reduction in pressure drop, leading to enhanced BTMS efficiency and reduced parasitic power [94]. However, GP methods are computationally intensive and require robust datasets for training.

Recently, generative AI diffusion models have been applied to optimize battery cell layouts, resulting in lower maximum battery temperatures and improved cooling efficiency [95]. Nevertheless, these models demand sophisticated implementation and validation processes.

Despite their potential, AI-based approaches face several challenges, including high computational requirements, complex model development, and the need for extensive datasets. In the context of battery temperature prediction and thermal management, advanced neural networks such as nonlinear autoregressive networks with exogenous inputs (NARX), long short-term memory (LSTM), and gated recurrent units (GRU) outperform traditional feed-forward neural networks (FFNN) and adaptive neuro-fuzzy inference systems (ANFIS) [70]. This is due to their superior handling of time-series data, which is critical in this domain.

A notable limitation in this field is the absence of standardized evaluation metrics. Researchers often need to compute multiple performance indicators to determine the most effective model for a given application [70]. Overall, while AI technologies offer significant advancements in battery thermal management, their implementation requires careful consideration of computational resources, data availability, and model complexity.

4. Cutting-Edge Strategies for Battery Thermal Management Systems (BTMS)

Advanced techniques are being explored to enhance Battery Thermal Management Systems (BTMS). Triply periodic minimal surface (TPMS) structures improve heat dissipation, while vibration-assisted BTMS boosts thermal performance. Flexible phase change materials (PCM) with skeletal reinforcement enhance stability, and additive manufacturing enables 3D-printed designs that optimize anisotropic properties. Nanoengineering is revolutionizing thermal regulation, and smart BTMS aims for ultra-low energy consumption. Bionic-inspired geometries further refine heat management, making BTMS more efficient and innovative.

4.1 Improved Heat Management Efficiency in Battery Thermal Management Systems (BTMS)

The integration of cutting-edge technologies is transforming Battery Thermal Management Systems (BTMS) by enhancing heat transfer, stability, and energy efficiency in electric vehicles. Triply Periodic Minimal Surface (TPMS) structures provide lightweight, high-surface-area designs that optimize thermal regulation, while vibration-assisted BTMS enhances cooling through improved fluid circulation. Flexible phase change materials (PCMs) reinforced with skeletal support ensure stability during phase transitions, maintaining consistent performance. Additive manufacturing and 3D printing enable the development of anisotropic structures optimized for efficient heat dissipation. Nanoengineered porous silica offers exceptional thermal insulation, reducing the risk of thermal runaway, while Smart BTMS employs self-regulating technologies to sustain ideal temperatures without additional energy consumption. Furthermore, nature-inspired bionic geometries introduce innovative cooling mechanisms, significantly improving BTMS effectiveness. These advancements collectively enhance the safety, reliability, and overall efficiency of electric vehicle battery systems.

4.1.1 Enhanced Thermal Performance through Triply Periodic Minimal Surface (TPMS) Structures

TPMS architectures offer highly porous, lightweight designs with exceptional surface area-to-volume ratios that significantly improve heat transfer and thermal conductivity capabilities, making them ideal for battery thermal management systems. Their performance advantages over conventional structures like metal foam have driven substantial research interest in recent years. The emergence of advanced additive manufacturing techniques has enabled widespread adoption of TPMS in thermal applications.

These TPMS-based configurations show considerable promise as high-efficiency internal structures for heat exchangers due to their exceptional surface-to-volume proportions, seamless surfaces, and intricate geometries [96]. Various TPMS-PCM composite configurations, including primitive, gynoid, and I-graph and wrapped packaged-graph (IWP) variations illustrated in Fig. 4(a), were analyzed using proprietary "MSLattice software" [96]. The thermal characteristics of these structures are directly influenced by unit cell type, porosity percentage, and porosity gradient distribution as these parameters affect surface area density. Different TPMS architectures demonstrate varying degrees of heat transfer enhancement, as depicted in Fig. 4(b).

Additional research by Zhaohui et al. [10] investigated liquid-cooled battery thermal management systems (BTMS) incorporating P-type TPMS sheet structures. The continuous, smooth surfaces characteristic of TPMS create extensive contact areas that enhance fluid-solid convective heat transfer. The liquid-cooled BTMS design methodology is outlined in Fig. 4(c). TPMS sheet structures are formed by joining two surfaces to create a single entity. The cooling channels within aluminum tubes contain arrays of these sheet structures, with semicircular tube surfaces positioned adjacent to the battery

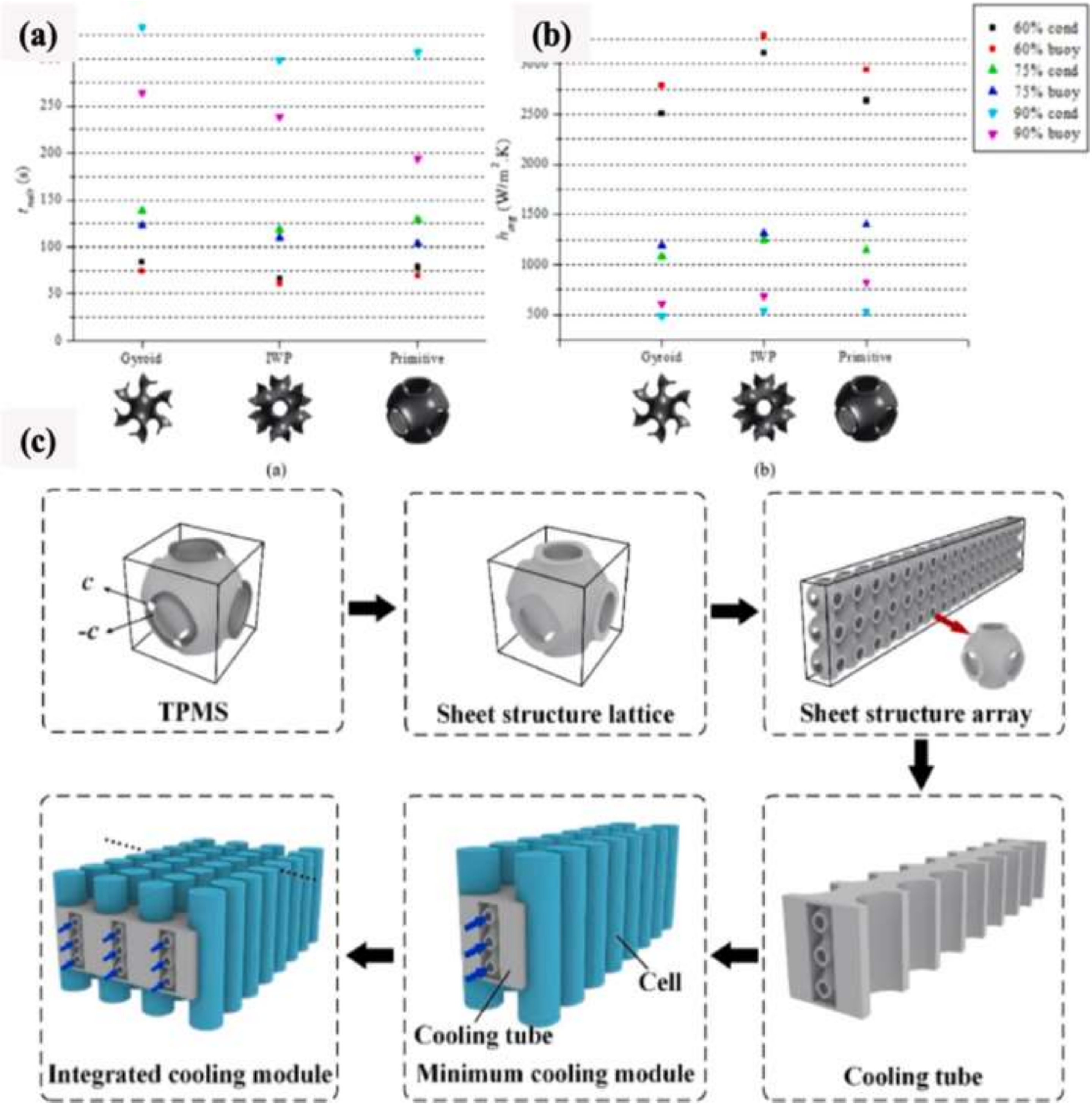


Figure 4: Unit cells of TPMS structures, including Primitive, Gyroid, and IWP, along with the impact of porosity on (a) the melting duration of phase change materials (PCM) and (b) the average heat transfer coefficient of TPMS-PCM composites.

cells. The complete cooling module comprises multiple parallel minimum cooling units. Implementation of gradient porosity-based sheet structures resulted in approximately 15.7% reduction in temperature differential across the module compared to uniform sheet configurations.

4.1.2 Enhanced Thermal Performance through Vibration-Augmented Battery Thermal Management Systems

Recent research has expanded to include real-world conditions by examining how vibration and shock impacts water-cooled Battery Thermal Management Systems (BTMS). Shukla et al. [97] conducted experiments under natural air convection for single-cell batteries with Phase Change Material (PCM)-based BTMS to simulate on-road vibration experiences. At the highest discharge rate (3C) and lowest frequency (10 Hz), vibration showed minimal effect on transient temperature distribution. However, as frequencies increased to 20 Hz and 30 Hz, vibration effects became considerably more significant.

For water-cooled mini-channel cold plate BTMS configurations, vibration demonstrated remarkable performance enhancement. Replacing a 1 mm radius fillet with a square cross-section in the original design improved overall efficiency by approximately 33.7%. The fundamental mechanism involves periodic vibration perpendicular to the primary flow direction, which effectively disrupts the temperature boundary layer. The resulting vortices promote mixing between high and low-temperature regions within the channels [98].

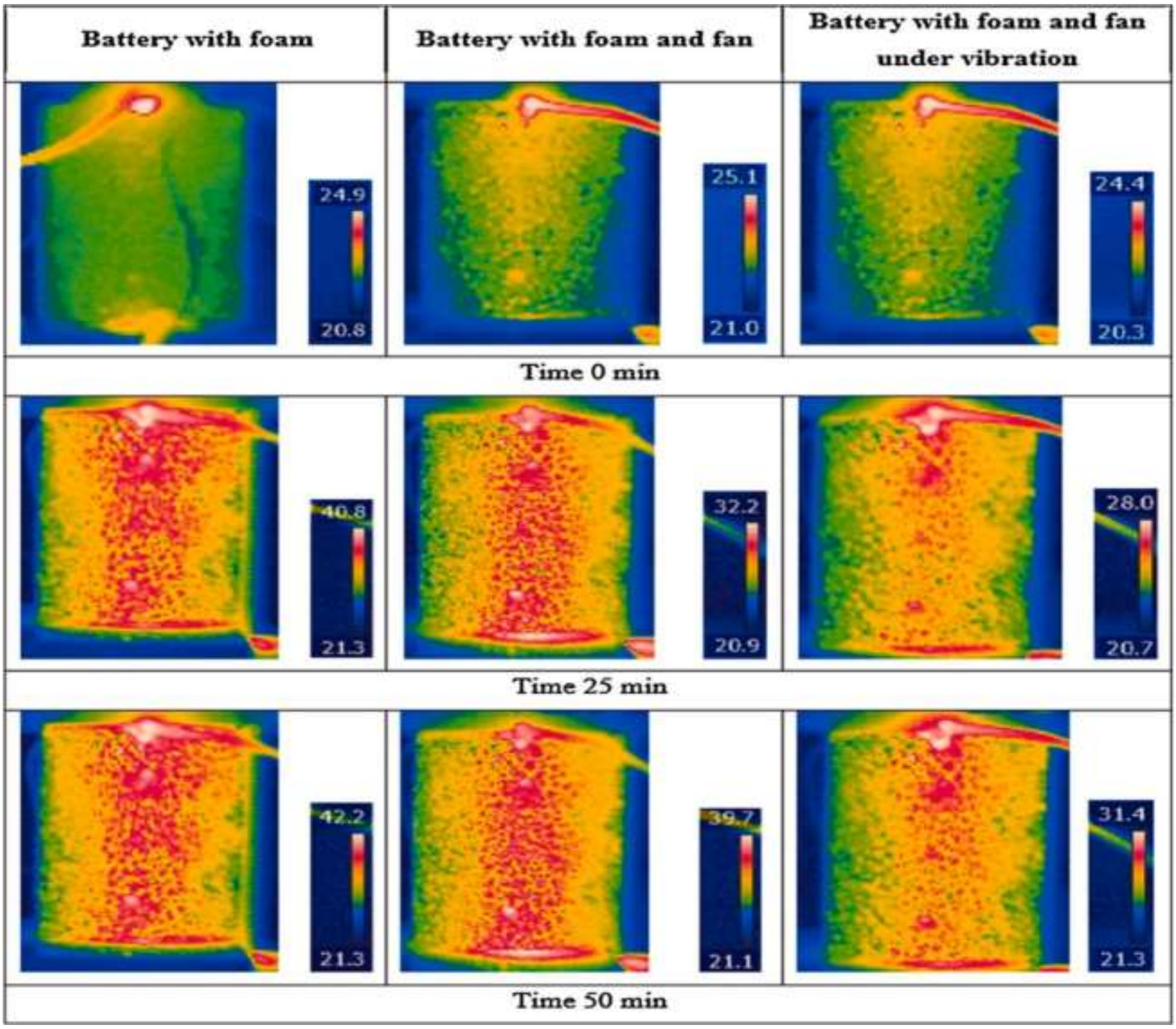


Figure 5: Thermal Analysis of Lithium-Ion Battery Across Different Cooling Setups

Research by Siddique et al. [33] investigated vibration effects on both natural and forced fan-based cooling of battery cells utilizing aluminum-based foam. As illustrated in Fig. 5 thermal imaging, surface temperatures with aluminum foam under forced convection decreased by 26°C compared to configurations without heat transfer media. When PCM remains in solid phase (below melting point), vibration effects are confined to the battery pack's exterior surface, making frequency and amplitude variations negligible regarding surface temperature [99].

At lower discharge rates, frequency demonstrates stronger influence on temperature increases. For higher discharge rates, both frequency and amplitude significantly impact temperature elevation. The researchers also recommended conducting vibration simulations specifically for off-road electric vehicles to address future mobility requirements in challenging terrain environments. Table 2 provides a comprehensive overview of current research findings related to vibration-enhanced BTMS implementations.

In summary, vibration substantially improves water-cooled BTMS performance, particularly at elevated frequencies, by enhancing heat transfer through boundary layer disruption. While effects remain limited at lower frequencies, they become pronounced in systems incorporating mini-channel cold plates and aluminum foam under forced convection conditions. This highlights the necessity for continued research in this domain, especially for demanding off-road applications.

Table 2

Research outcome of Vibration enhanced BTMS systems.

Mode of BTMS	Vibration Variables	Battery Type	Discharge Rates	Research outcome
Vibration enhanced Natural Air Cooled [97]	10 Hz, 20 Hz, and 30 Hz, 40 mm/s, 55 mm/s, and 70 mm/ s	18,650 lithium-ion battery (Model: Samsung 26FM-PCB,	1 C, 2 C, and 3 C	There is no distinct correlation was observed between vibration amplitude, frequency, and transient temperature distribution.
Water cooled [98]	10 Hz, 0.8 mm	-	1 C, 2 C, and 3 C	The cold plate’s overall performance increased by 33.7 % with a f illet radius of 1.0

				mm compared to its original square cross-section.
Rubitherm® 35HC PCM [99]	20–30 Hz, 30 mm/s to 50 mm/s	Simulated battery pack which mimics 2300 mAh 18,650	1 C to 5 C	Improved heat transfer from the battery pack due to vibrations.
Porous aluminium foam medium, grade: 6101 alloy-T6 [33]	5 Hz, 10 Hz, and 15 Hz), 10 mm/s, 20 mm/s, and 30 mm/ s	Single Cell, 18,650 Li- ion battery (model: 26FM-PCB; Samsung	1 C, 2 C, and 3 C	The Li-ion battery cools down significantly faster when subjected to forced convection in aluminium foam under vibration.

4.1.3 Enhanced Thermal Regulation through Structurally-Reinforced Flexible Phase Change Materials

Materials such as styrene-butadiene-styrene (SBS) and thermoplastic ester elastomer (TPEE) serve as advanced structural frameworks and integrated packaging components, significantly enhancing the deformation capabilities and flexibility of composite phase change materials (CPCMs). This engineering approach results in innovative, form-stable, flexible CPCMs with excellent thermal energy storage capacity. The incorporation of expanded graphite (EG) further improves heat dissipation efficiency and promotes a more uniform temperature distribution throughout the material [100].

Experimental results indicate that these advanced CPCMs maintain consistent mechanical performance under various deformation modes, including bending and stretching, while exhibiting superior physical and chemical compatibility with battery system components [100]. For large-scale production of leak-resistant CPCMs, researchers have developed phase-transformable, hydrophobic polymer matrices synthesized in situ within paraffin (PA)/expanded graphite composites [101]. These advanced CPCMs exhibit outstanding thermal properties, achieving latent heat values of 120.3 J g^{-1} and thermal conductivity of 2.92 W m^{-1} K^{-1}, primarily due to the additional thermal storage contribution from phase-transformable alkyl side chains in the polymer framework.

The engineered CPCMs demonstrate exceptional dimensional stability at elevated temperatures of up to 250°C, along with superior paraffin retention properties. These performance characteristics are attributed to the three-dimensional cross-linked structure of primary polymer chains, reinforced by hydrophobic alkyl side branches. When integrated into Battery Thermal Management Systems (BTMS), these structurally reinforced, flexible phase change materials significantly enhance thermal regulation by maintaining material integrity throughout numerous thermal cycles, effectively preventing leakage and structural degradation. The embedded reinforcement framework provides essential mechanical support while preserving flexibility, ensuring consistent thermal conductivity and heat absorption across different operational conditions.

4.1.4 Optimized Thermal Performance through Additively Manufactured Battery Thermal Management Systems

The transformative potential of additive manufacturing (AM) technologies marks a paradigm shift in the design of thermal management devices. The integration of 3D printing with advanced two-dimensional materials, such as graphene and boron nitride (BN), unlocks unprecedented opportunities for fabricating programmed hierarchical structures with optimized thermal properties. Experimental results, combined with finite element analysis, demonstrate that selective laser sintering (SLS) 3D-printed phase change materials (PCMs) incorporating expanded graphite (EG), can achieve significant thermal regulation capabilities comparable to traditional press-and-soak manufacturing methods [102].

Graphene-enhanced thermally conductive composites produced through 3D printing have exhibited exceptional thermal conductivities reaching up to 12 $Wm^{-1}K^{-1}$ [103]. This remarkable thermal performance is primarily attributed to the anisotropic structural arrangement, which optimally aligns graphene's high thermal conductivity. Additionally, 3D printing enables the design of advanced coolant flow channels within battery packs, facilitating higher heat transfer coefficients. The improved heat dissipation at the coolant interface is particularly advantageous, as it allows the integration of materials with lower thermal conductivity in these regions while maintaining efficient cooling.

Researchers have also leveraged 3D printing to fabricate high-performance thermal management structures, including biomimetic heat sinks inspired by the morphology of shark skin. These designs incorporate regularly arranged hollow elevated ridges that optimize thermal convection, offering innovative nature-inspired solutions that are challenging to achieve through conventional manufacturing techniques [104].

Furthermore, Lu et al. [106] explored thermal insulation architectures developed using additive manufacturing. Their research investigates AM-enabled hierarchical structures that provide both thermal insulation and mechanical resilience. The integration of 3D-printed silica components, combining polymer networks with porous silica, results in super-elastic structures featuring low thermal conductivity and tunable mechanical properties. These innovative materials have promising applications in Battery Thermal Management Systems (BTMS) by minimizing thermal aging effects and enhancing the overall thermal stability of lithium-ion batteries.

As depicted in Fig. 6, researchers examined direct ink writing (DIW) 3D-printed silica-based (silivoxel) battery enclosures

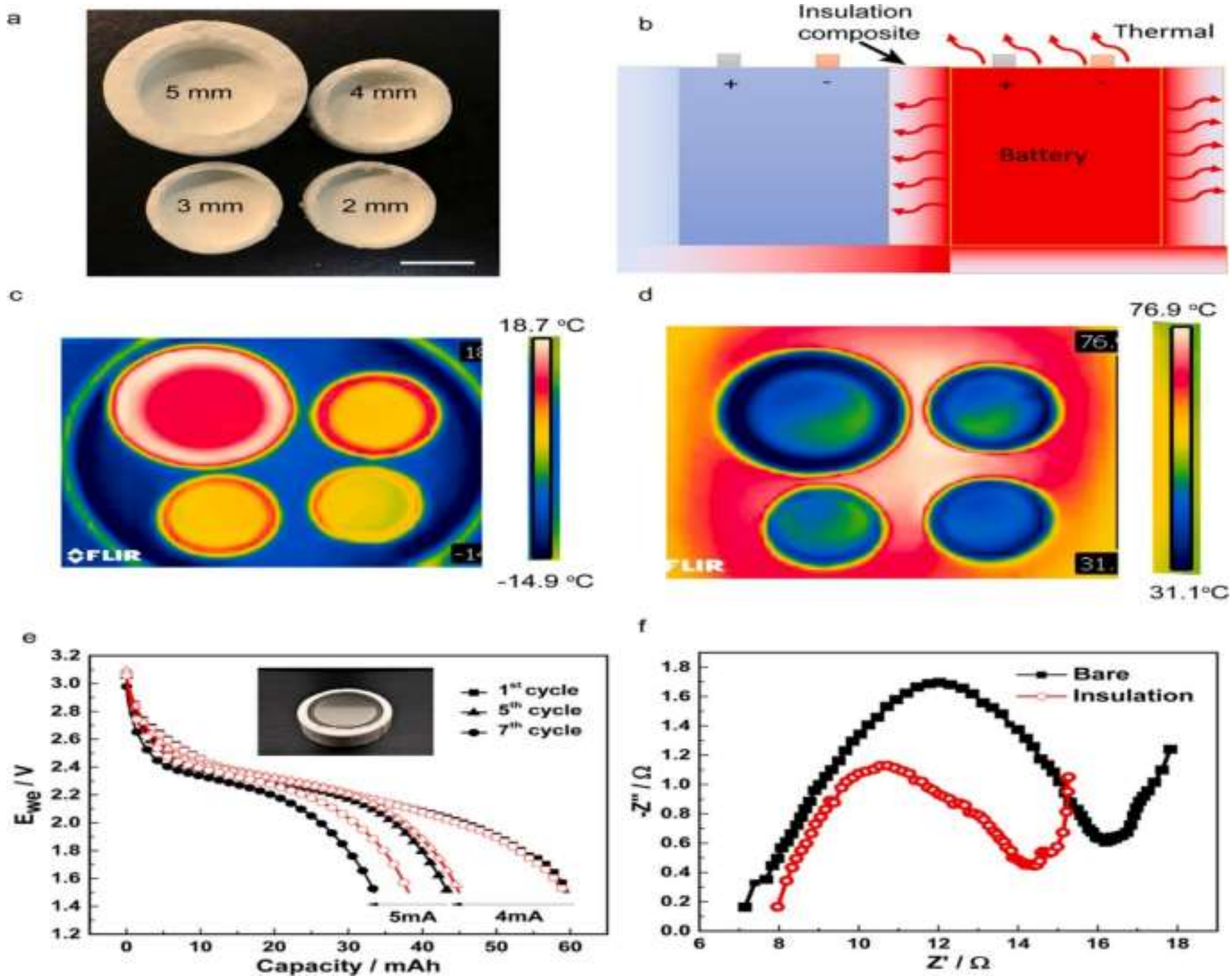


Figure 6: Thermal Performance Analysis of DIW-Silivoxel Battery Casings (a) The DIW-silivoxel battery enclosures are available in thicknesses of 2 mm, 3 mm, 4 mm, and 5 mm, with a 10 mm scale bar for reference. (b) Illustration of the thermal mitigation strategy for the battery pack. (c, d) Infrared (IR) thermal images displaying DIW-silivoxel enclosures of different thicknesses placed on surfaces at varying temperatures—cold (76.9°C) and hot conditions (76.9°C). (e) Lithium-ion battery charging profiles at temperature C, comparing cases with thermal protection (open symbols) and without protection (closed symbols) using DIW-silivoxel enclosures [106].

with varying thicknesses, including 2 mm, 3 mm, 4 mm, and 5 mm, to evaluate their thermal insulation performance. Infrared (IR) thermographic imaging confirms the effectiveness of silivoxel-based enclosures in providing thermal mitigation. Battery charge-discharge cycling at elevated temperatures (70°C) demonstrated enhanced thermal protection, as evidenced by the temperature profiles. Additionally, Nyquist plot analysis indicates improved thermal stability for batteries equipped with DIW-silivoxel enclosures, underscoring their potential for enhanced performance in thermally demanding applications.

4.1.5 Advanced Thermal Regulation through Nanoscale Engineering

Nanoscale engineering has emerged as a pivotal strategy for enhancing Battery Thermal Management System (BTMS) efficiency. By implementing materials and structures at the nanometer scale, researchers have achieved significant improvements in reliability and thermal dissipation capabilities that address fundamental challenges in battery performance and safety. The most prominent nanoscale engineering applications include nanofluidic-based BTMS, heat pipes containing nanofluids, and phase change materials enhanced with nanoparticles [8,107].

While liquid cooling remains a fundamental approach in BTMS design, thermal media with advanced properties has become an increasingly active research domain [108]. Researchers create nanofluids by incorporating micro and nano-sized metallic or metal oxide particles into base liquids such as water or ethylene glycol to significantly enhance thermal conductivity [108-111]. Multiple variables influence nanofluid performance, including particle composition, morphology (cubic, rod-shaped, spherical), dimensions, volumetric concentration, and effective surface area [108]. Additional factors affecting nanofluid performance include surfactant addition, pH regulation, and ultrasonic processing [108]. Common nanoscale additives include Cu, CuO, MgO, Al_2O_3, TiO_2, ZnO, AgO, and ZrO_2 [109,112-115]. Among these variables, the volumetric concentration of nano and micro-sized particles represents a critical parameter affecting nanofluid thermal conductivity [108,116]. Research examining cooling performance of nanofluids containing TiO_2 nanoparticles at 0.25% and 0.5% volumetric concentrations demonstrated temperature reductions of up to 28.65% compared to conventional cooling modules [117].

Heat pipes represent another BTMS application where nanofluids demonstrate significant potential. In these systems, thermal energy absorbed during evaporation is subsequently released during condensation through working fluid phase transformation. Despite their inherent effectiveness, heat pipes are typically integrated with air or liquid cooling systems to maximize performance [109,118,119]. Water cooling at the heat pipe condenser remains a standard approach in thermal management systems. However, numerous studies have explored heat pipes utilizing water-based nanofluids containing various nanoparticles including Al_2O_3, TiO_2, carbon nanotubes (CNT), and graphene oxide (GO) [120-123]. Research indicates that implementing Al_2O_3-based nanofluids at 1.5% volumetric concentration in heat pipes can reduce battery thermal resistance by approximately 15% [123].

Beyond nanofluid applications, nanoparticles and nanofibers have demonstrated significant improvements in Phase Change Material (PCM) thermal properties [1,107,109,124]. This PCM enhancement approach is designated as nanoparticle-enhanced PCM (NEPCM). Extensive research has investigated factors influencing NEPCM performance, including nanoparticle type, morphology, size, volumetric concentration, and physicochemical characteristics [107,109,124]. Integrating nanoscale materials into PCMs enhances thermal properties through their extensive surface area, which significantly improves heat exchange efficiency. Additionally, their dispersion throughout PCMs creates effective thermal exchange pathways that facilitate efficient heat dissipation [124].

Nanoscale engineering also enables development of porous frameworks providing effective thermal runaway mitigation for battery systems. This approach extends to creating super-thermal insulation for energy-critical applications, beginning with transformation of mesoporous silica into nanocage silica structures for superior thermal insulation against thermal runaway events. Research demonstrates that cross-linking ceramic fibers with porous silica frameworks achieves a tensile Young's modulus of 2.8 MPa while maintaining exceptional thermal insulation properties [125]. Additional work has explored silicone grease/composite phase change materials incorporating polyethylene glycol/boron nitride/expanded graphite (CPCM). This approach addresses the significant contact resistance created by conventional CPCM's uneven surfaces. Compared to standard CPCM, the silicone-enhanced composite phase change material (SCPCM) exhibits superior dimensional stability and significantly reduced contact thermal resistance [126].

4.1.6 Intelligent Thermal Management for Ultra-Efficient Energy Conservation

Traditional thermal management systems require considerable energy consumption, relying on components such as pumps, refrigerants, and control electronics in active cooling setups. In this context, the term "near-zero energy" describes the minimal external power needed to regulate battery temperature using the sorption-induced thermal effects of metal-organic frameworks (MOFs). To maintain battery temperature in both hot and cold conditions, researchers have introduced an innovative Smart Battery Thermal Management (SBTM) approach with near-zero energy consumption [127]. The system autonomously adjusts heating or cooling based on the sorbent’s water sorption or desorption states, responding directly to the local battery temperature. When overheating occurs, water vapor desorption absorbs excess heat, thereby cooling the battery. Conversely, during cold conditions, sorption releases heat, warming the battery. These reversible thermal effects enable passive cooling and heating without requiring additional energy input.

The proposed self-adaptive SBTM achieves a compact, liquid-free, high-power-density thermal management system. It effectively operates under varying conditions with the aid of MIL-101(Cr)-based carbon foam MOFs ($Cr_3F(H_2O)_2O[(O_2C)C_6H_4(CO_2)]_3 \cdot nH_2O$), which harvest sorption energy from the surrounding air to facilitate temperature regulation [28,128]. As illustrated in Fig. 7(c), the passive heating and cooling mechanism utilizes reversible water vapor sorption/desorption to trigger endothermic and exothermic reactions without external energy input.

Furthermore, a hybrid BTMS was developed by integrating a nickel-titanium (NiTi) shape memory alloy (SMA) actuated smart wire with a phase change material (PCM) containing expanded graphite (EG) to enhance thermal regulation in both hot and cold operating conditions [129]. The system incorporates an aluminum casing (depicted in Fig. 7(a)), which encloses the EG-PCM medium. The NiTi SMA wire’s functionality is based on its temperature-dependent behavior, adjusting its length in response to thermal fluctuations. When the battery reaches its upper temperature limit, the SMA wires contract, closing the gap between the battery and the aluminum-cased PCM-EG BTMS (on-mode). This configuration facilitates heat dissipation via conduction and convection. As the battery cools, the NiTi SMA wires revert to their original length, restoring the separation between the battery and BTMS (off-mode), effectively maintaining the battery temperature within the desired range.

In conclusion, Smart Battery Thermal Management (SBTM) systems, leveraging advanced materials such as MOFs and nickel-titanium shape memory alloys, provide an energy-efficient, self-regulating solution for battery temperature control. By autonomously modulating heating and cooling cycles, these systems enhance battery performance, improve thermal stability, and ensure optimal operating conditions—all without requiring additional energy input.

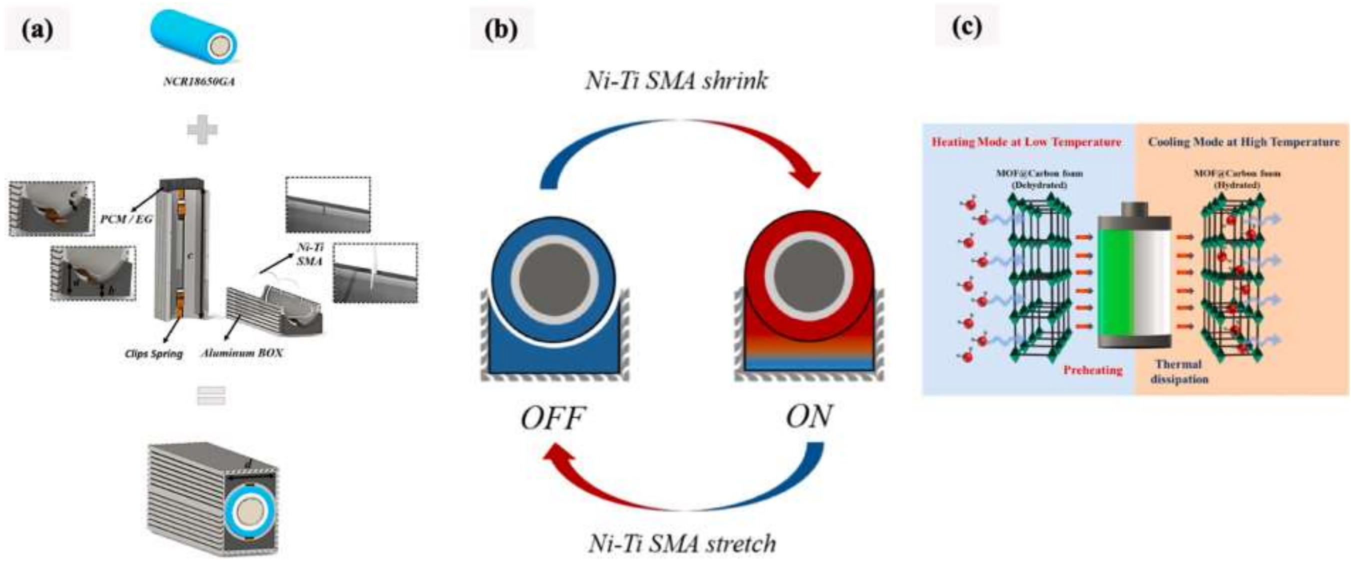


Figure 7: The Smart Battery Thermal Management (SBTM) system operates through multiple mechanisms to regulate battery temperature efficiently. It utilizes (a) an attach-detach mechanism in which an aluminum casing with EG-PCM aids in battery cooling, facilitated by (b) a Shape Memory Alloy (SMA) that expands and contracts to adjust thermal contact [129]. Additionally, (c) reversible water sorption in metal-organic frameworks (MOFs) enables passive heating and cooling without external energy input [28]. These innovations contribute to effective, energy-efficient thermal regulation.

4.2 Cutting-Edge BTMS Strategies for Hazard Prevention

4.2.1 Mist-Based Approach for Hazard Prevention

In recent years, air cooling efficiency has been significantly improved through an innovative two-phase fluid cooling technique, which combines fine water droplets with air for battery temperature regulation [137–140]. This method not only enhances thermal management but also serves as an emergency hazard mitigation system, preventing thermal runaway (TR) and acting as a fire suppression mechanism [141,142].

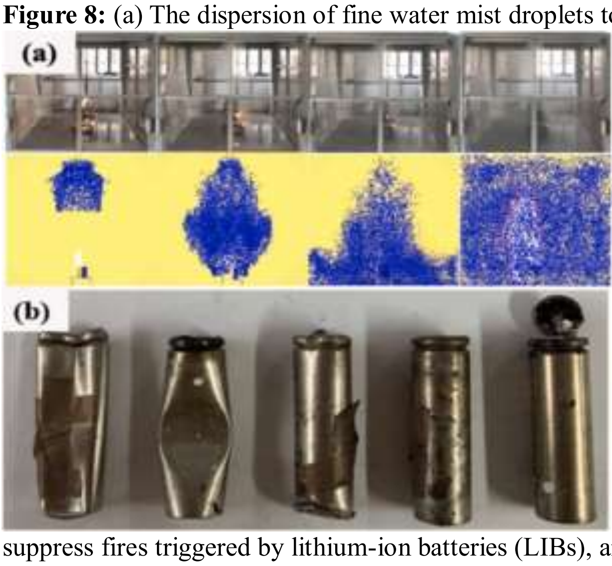
Current research explores the impact of various additives on fire extinguishing efficiency, focusing on their physicochemical roles. Physical additives enhance heat absorption, cooling efficiency, radiation heat shielding, and oxygen displacement by reducing droplet size and surface tension in the mist. Meanwhile, chemical additives improve fire suppression by breaking down carbon dioxide and water in the combustion zone and capturing free radicals during battery ignition. Studies have utilized non-ionic surfactant decyl glucoside and anionic surfactant sodium dodecylbenzene sulfonate to optimize these effects [143].

The evaporation of fine water mist droplets at 90°C and 101 kPa generates a gaseous phase, leading to oxygen displacement within the high-temperature combustion zone. Numerical simulations using Fire Dynamics Simulator (FDS) (Fig. 8a) illustrate that as the mist vaporizes, it diffuses against the incoming oxygen flow, reducing oxygen availability near the flame. Additionally, a protective inert barrier forms on the cell's surface, preventing fuel-oxygen interaction and thereby mitigating combustion.

J. Xu, Q. Duan, L. Zhang et al. [142] identified four distinct cooling phases of water mist application: (a) rapid cooling followed by quasi-steady-state cooling, (b) rapid then gradual cooling, (c) transitional phase, and (d) rapid heating followed by rapid cooling. During the initial mist evaporation phase, the mist rapidly vaporizes upon contact with the hot, dry battery surface, resulting in immediate cooling. As shown in Fig. 8b, continuous mist application eventually forms a liquid film, further lowering the cell temperature. However, in the final cooling stage, the cooling rate decreases. If thermal runaway (TR) occurs, the Leidenfrost effect is triggered, creating a vapor layer that prevents direct mist contact with the battery surface, reducing evaporation efficiency [142].

Additionally, research highlights that three operational modes govern water mist behavior: (i) rapid mist evaporation upon contact with a high-temperature cell, (ii) liquid film formation due to continuous mist spraying, and (iii) a gradual decrease in cooling rate in the final stage [142]. Other studies have shown that under a spray-cooling mode of 4 + 2.5 m/s, the overall heat transfer coefficient (K) reaches 201.0 W/(m²·K)—a 409.3% improvement over traditional forced air cooling techniques [144].

Figure 8: (a) The dispersion of fine water mist droplets to



suppress fires triggered by lithium-ion batteries (LIBs), and (b) the condition of the batteries following the combustion experiment [143].

5. Sustainable Approaches in Battery Thermal Management Systems (BTMS)

Effective battery thermal regulation is fundamental to the long-term viability of battery technologies, as it directly impacts ecological integrity, social well-being, and financial feasibility. This interconnectedness is apparent throughout the operational lifespan of battery thermal management systems (BTMS). For example, enhanced operational security and performance minimize adverse ecological impacts and potential societal hazards, while simultaneously decreasing overall expenditures. Consequently, a strategic emphasis on sustainable material selection for BTMS, coupled with environmentally conscious manufacturing practices and robust end-of-life reclamation strategies, harmonizes these critical dimensions with internationally recognized sustainable development goals (SDGs).

5.1 Environmental Sustainability of BTMS

The global transition towards electrification and increasingly stringent sustainability mandates necessitates a paradigm shift in automotive manufacturing, compelling producers to implement eco-conscious design principles across the vehicle's entire lifecycle. Optimized battery thermal management systems (BTMS) are pivotal in diminishing the carbon footprint of electric vehicles (EVs), thereby contributing to a substantial reduction in greenhouse gas emissions. This is achieved through the enhancement of battery performance and the prolongation of battery lifespan, which in turn minimizes the frequency of replacements and the associated emissions [150]. By maintaining batteries within optimal thermal parameters, effective BTMS augment energy conversion efficiency, consequently lessening the ecological burden linked to energy consumption [151]. Furthermore, the production and end-of-life management of batteries present substantial environmental challenges, including heavy metal contamination and resource depletion; however, advancements in BTMS offer a pathway to alleviate these concerns by extending battery longevity and maximizing operational efficiency [152]. The incorporation of environmentally benign working fluids and materials within BTMS, such as heat pipes and phase change materials (PCMs), plays a crucial role in mitigating adverse ecological impacts [153]. Moreover, the synergistic integration of renewable energy sources with battery systems supports broader decarbonization initiatives [154]. Ultimately, meticulous thermal regulation minimizes the holistic lifecycle environmental footprint of batteries by enhancing their operational effectiveness and durability, thereby curtailing emissions associated with both manufacturing and disposal phases [155].

5.2 Societal Implications of BTMS

The development and implementation of sustainable thermal management solutions are significantly influenced by factors such as safeguarding health and safety, fostering economic contributions that mitigate supply chain vulnerabilities, and promoting responsible social behaviors. Effective Battery Thermal Management Systems (BTMS) play a crucial role in ensuring the safe operation of batteries by preventing thermal runaway and fire hazards, which are paramount for user safety, particularly in urban environments [156]. Electric vehicles **(EVs), through their contribution to improved air** quality, thermal comfort, and reduced pollution, align with Sustainable Development Goal (SDG) 3, enhancing health and well-being. Furthermore, EV-based hybrid energy systems can address energy reliability challenges [157]. The sourcing and processing of battery materials, including lithium and cobalt, have substantial social consequences, impacting supply chain dynamics, labor conditions, and community well-being. Implementing sustainable supply chain practices is essential for mitigating these risks [158]. Societal responsibility for sustainability is another critical dimension, as collective choices and behaviors, such as consumption patterns and policy formulation, can either protect or degrade environmental resources and influence economic systems. Finally, advancements in BTMS technologies enhance the performance of EVs, resulting in improved user experiences regarding vehicle range, charging efficiency, and overall reliability [159].

5.3 Economic Implications of BTMS

The economic dimensions of Battery Thermal Management Systems (BTMS) center on achieving cost-effectiveness, minimizing lifecycle expenses, incentivizing innovation investments, and bolstering market competitiveness, thereby generating long-term economic advantages for manufacturers, consumers, and the electric vehicle (EV) sector. The diverse range of BTMS technologies, including air cooling, liquid cooling, and heat pipes, presents varying cost considerations [151]. Implementing effective BTMS can yield substantial economic benefits by reducing maintenance expenditures and extending battery longevity, benefiting both producers and end-users [160]. The advancement and optimization of BTMS necessitate significant capital allocation towards research and development [161]. Simulation analyses indicate that the integration of BTMS with complementary systems, such as power-to-heat, can further enhance economic viability [162]. While initial investments may be substantial, they promise long-term economic returns through improved battery performance and reduced operational costs [27]. Ultimately, advanced BTMS technologies can strengthen the market competitiveness of EVs by enhancing performance, reliability, and cost-efficiency, all of which are critical drivers for consumer adoption and market expansion.

6. Advanced Methodologies for Thermal Regulation in Batteries

6.1 Combined Cooling Methodologies

Innovative advancements in battery cooling technologies are revolutionizing thermal management strategies, enhancing efficiency, safety, and sustainability. Cutting-edge techniques, such as liquid immersion cooling, advanced phase change materials (PCMs), and nanofluid-based cooling, are being explored to improve heat dissipation. Additive manufacturing enables the design of intricate cooling structures, optimizing thermal regulation while reducing weight and material usage. Additionally, the integration of artificial intelligence (AI) and machine learning facilitates real-time temperature monitoring and adaptive cooling strategies. These emerging technologies are shaping the future of battery thermal management, ensuring enhanced performance and extended battery lifespan in various applications.

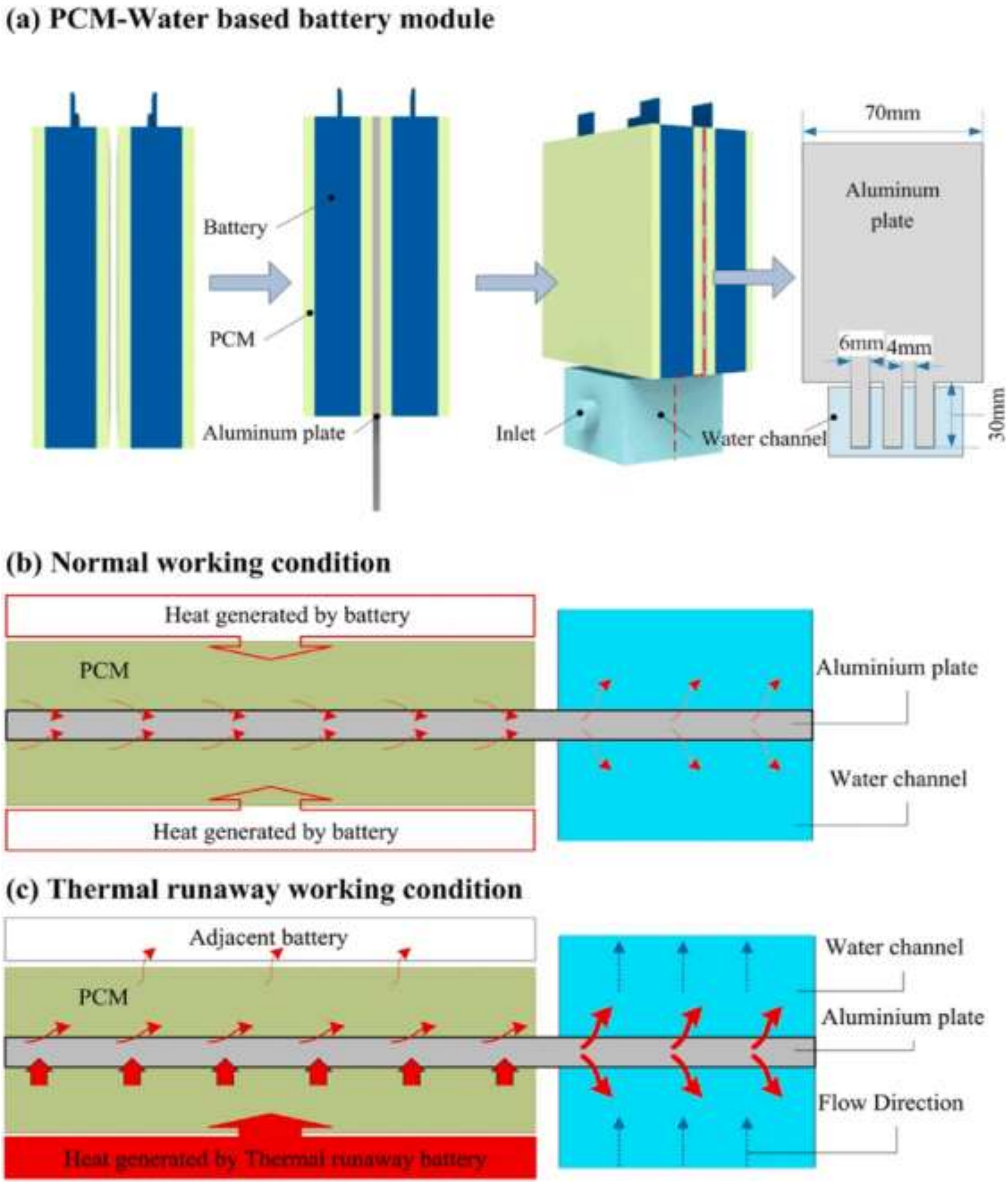


Figure 9: BTMS schematic, illustrating: (a) its design, (b) normal heat flow, and (c) heat transfer during thermal runaway

6.1.2 Integration of Liquid Cooling, Phase Change Materials, and Heat Pipes for Thermal Management

Yang et al. [163] developed a hybrid liquid cold plate featuring Z-type parallel cooling channels, a PCM/aluminum foam composite, and a delayed cooling mechanism. Their findings revealed that this optimized cold plate design, which weighs 50% less than the conventional version, reduces total pumping power by over half while maintaining effective thermal regulation, keeping battery temperatures below 40°C at discharge rates of 1C, 2C, and 3C. Similarly, Liu et al. [164] proposed an advanced hybrid cooling system combining PCM/copper foam and helical liquid channels, demonstrating a battery temperature reduction of over 30 K compared to natural convection.

In another approach, Weng et al. [165] designed a hybrid cooling system incorporating heat pipes embedded in PCM, leveraging both forced and natural convection for battery thermal regulation. Zhang et al. [166] explored the integration of PCM and liquid cooling to contain thermal runaway in battery modules. For prismatic batteries, Hekmat and Molaeimanesh [167] introduced a sandwich-structured cooling system embedding water pipes within PCM, significantly enhancing temperature uniformity. Meanwhile, Wu et al. [168] utilized PCM within the gaps between cylindrical batteries, integrating a mini-channel cold plate beneath the battery module for improved cooling.

Further research by Akbarzadeh et al. [169] investigated hybrid liquid/PCM cold plates for prismatic battery modules, incorporating a liquid cooling plate into PCM and affixing hybrid cooling plates at both ends of the battery pack. Their study found that this configuration provided effective cooling throughout operational cycles and acted as a thermal runaway barrier. Hybrid cold plates demonstrated up to 30% lower coolant pumping power than active cooling systems while significantly enhancing temperature uniformity.

(a)

(b)

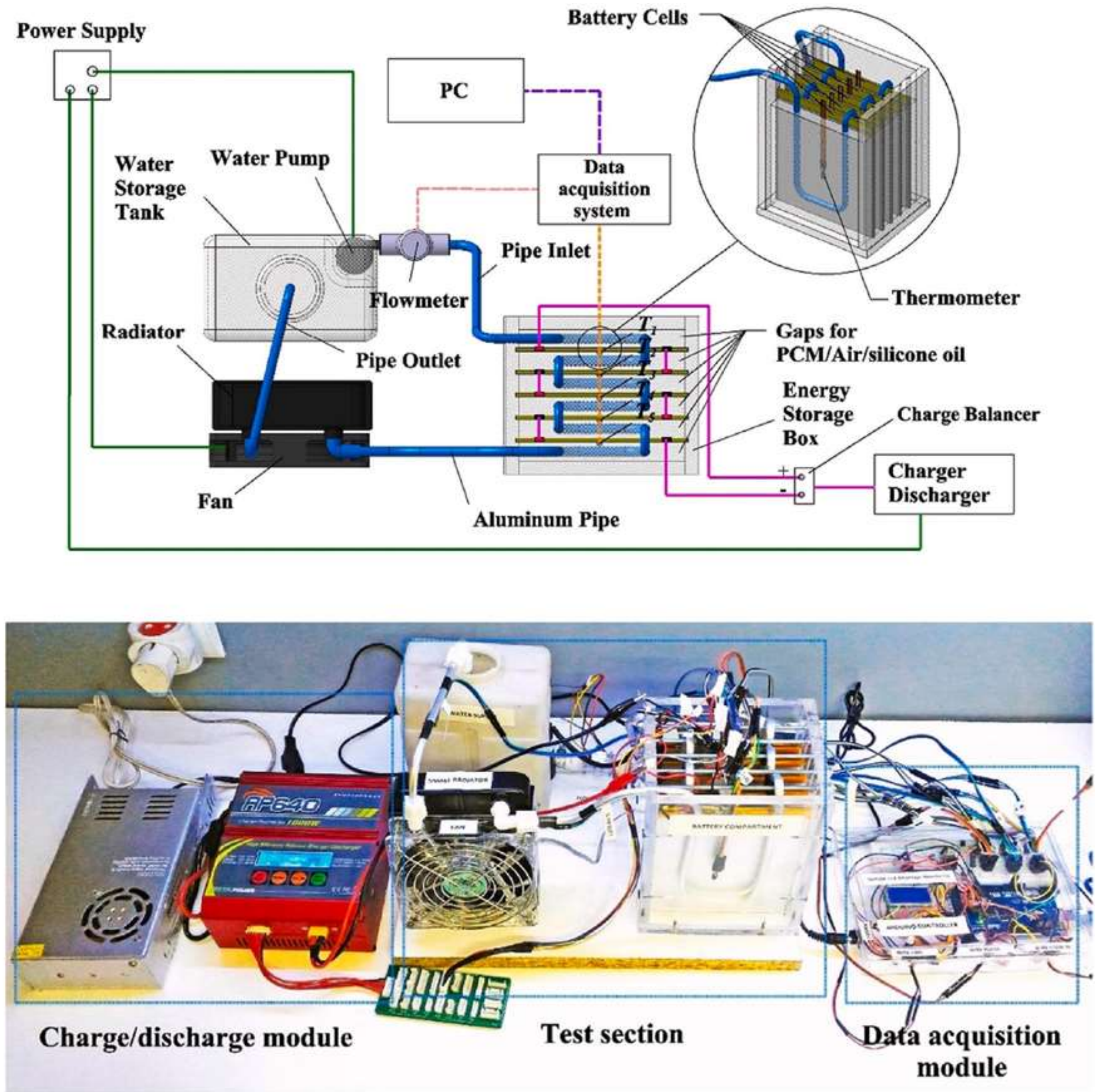


Figure 10: Integrated PCM-Liquid Cooling Thermal Management System (Dual-mode battery thermal regulation solution featuring: (a) conceptual diagram illustrating the architectural configuration of the combined phase change material and liquid cooling arrangement; (b) photographic representation showing the physical implementation of the hybrid system [167].

Cao et al. [170] advanced a PCM-based hybrid cold plate with a delayed cooling strategy, ensuring temperature uniformity while reducing energy consumption. Meanwhile, Hu et al. [171] examined the influence of pump start-up time, flow rate, and intake temperature on battery thermal and electrical performance, developing a hybrid cooling system that dynamically balances passive and active cooling. Their findings suggest that passive cooling meets heat dissipation demands under moderate conditions, with active liquid cooling required only in extreme situations, such as 3C discharge at 35°C.

Mousavi et al. [172] proposed a novel hybrid cooling method incorporating PCM and liquid cooling for prismatic battery modules. In their setup, battery cells were arranged between vertically oriented mini-channel cooling plates. Empirical and numerical studies confirmed that at 2C and 3C discharge rates, the maximum battery temperature in the hybrid system using three PCM plates was reduced by 5.6 K and 16.2 K, respectively, compared to systems without PCM. Furthermore, temperature differentials decreased by up to 33% at 3C discharge with the inclusion of PCM plates. The system also improved emergency thermal management, with PCM-enhanced modules extending the time to reach critical temperatures by 38% (one PCM plate) and 105% (three PCM plates). Additionally, power consumption per battery cell dropped by 68% at 3C discharge.

Rao et al. [173] conducted a numerical investigation of a PCM/mini-channel hybrid BTMS, analyzing flow rates, material properties, and mini-channel configurations. Their findings highlighted that the PCM's thermal conductivity and melting point significantly influence its phase transition efficiency. They identified optimal parameters for PCM integration, recommending a melting temperature of 308.15 K and a thermal conductivity of 0.6 W/m·K. Their results showed that the peak temperature in the hybrid BTMS was 320.6 K, significantly lower than the 335.4 K observed in PCM-only systems.

Table 3 summarizes research on hybrid cooling systems incorporating liquid cooling, PCM, and heat pipes for BTMS applications. These studies underscore the improvements in cooling efficiency, energy conservation, and thermal stability achieved through hybrid approaches, contributing to enhanced battery performance, safety, and longevity.

6.1.3 Integration of Air Cooling, Phase Change Materials, and Heat Pipes for Thermal Management

Heat pipes and phase change materials (PCMs) have attracted significant commercial attention as passive thermal management solutions requiring no additional power input for applications including heat recovery, solar energy collection, electronics cooling, modern industrial processing, aerospace systems, and battery thermal management [174]. Sharma et al. [175] presented a comprehensive analysis of air-cooled and air-centric hybrid battery thermal management systems (BTMS). Their work examined thermal performance across various designs and operating conditions, comparing system effectiveness in reducing maximum temperatures and minimizing temperature gradients within battery modules. The research aimed to provide practical guidelines for developing air-cooled hybrid systems that require minimal resources and complexity, thereby reducing parasitic power consumption.

Dan et al. [176] developed an innovative hybrid BTMS combining air cooling with micro heat pipe arrays and proposed a corresponding thermal model utilizing circuit analysis principles. Their findings demonstrated that natural air convection integrated with micro heat pipe arrays maintained battery temperatures below 40°C at 1C discharge rates, while 3 m/s airflow achieved similar results at 3C discharge rates. Post-discharge temperature variations between cells remained below 2°C. The superior thermal performance resulted from increased effective heat transfer contact area, the exceptional heat transfer capacity of heat pipes, and rapid heat absorption capabilities during high-rate discharge conditions.

Ling et al. [177] addressed heat accumulation challenges in PCM systems with inadequate natural air convection through experimental investigation of a hybrid configuration (forced air combined with PCM) for lithium-ion battery packs undergoing cyclical charging/discharging. Their hybrid system successfully maintained battery temperatures below 45°C throughout all five test cycles, while passive PCM-only systems achieved acceptable performance for only the first two cycles, particularly at higher discharge rates. Additional investigation into airflow velocity effects revealed that 3 m/s proved sufficient for maintaining lithium-ion battery temperatures within specified operational ranges.

Situ et al. [178] engineered the using dual copper mesh reinforcement with PCM plates for prismatic lithium-ion battery modules generating substantial thermal loads. The maximum recorded temperature reached 55°C using the double copper mesh PCM configuration at 5.2C discharge rate with optimized 6 m/s airflow velocity. Wu et al. [179] manufactured advanced ternary paraffin+expanded graphite+copper mesh PCM composites and developed a hybrid thermal management system addressing limitations of binary paraffin/expanded graphite PCMs, including insufficient thermal conductivity, inadequate structural integrity, and module deterioration during repeated phase transition cycles. While PCM-only systems recorded maximum temperatures of 81.9°C, the hybrid configuration maintained peak temperatures at 55°C with temperature differentials of only 2°C across charge/discharge cycles. This performance enhancement resulted from copper mesh integration, which significantly improved thermal conductivity.

Rectangular PCM configurations demonstrated superior cooling performance due to uniform air channel distribution. Results indicated comparable thermal regulation between circular and hexagonal PCM arrangements. Optimized airflow at 0.2 m/s increased cooling efficiency by 624% compared to natural convection. Battery pack architecture and cell configuration emerged as critical factors affecting overall cooling performance.

Bamdezh et al. [185] conducted quantitative analysis of hybrid BTMS performance using various configurations, examining effects of cell density, arrangement patterns, and PCM thickness. Results demonstrated that increased PCM thickness, staggered cell arrangements, and greater intercellular spacing enhanced cooling performance due to increased thermal capacity. Temperature variations between battery cells remained below 1.5°C across all test scenarios, confirming the hybrid system's capability to maintain temperature uniformity. Lv et al. [186] developed an innovative hybrid BTMS with forced air convection for battery modules, introducing serpentine composite phase change materials (S-CPCM) to enhance heat dissipation capabilities compared to conventional block-shaped CPCM (B-CPCM). Maximum temperature decreased from 54.2°C to 51.9°C at identical fan speeds while using 70% less phase change material and increasing energy density by 13.8 Wh/kg. This remarkable improvement in thermal efficiency with reduced PCM usage resulted from increased contact surface area with cooling media.

Table: 3

Study	Configuration and Methodology	Key Findings
Yang et al. [163]	Z-type parallel cooling channels with PCM/ aluminum foam composite	Reduced total pumping power by >50%, maintained average battery temperature within 40 ◦ C for discharging rates of 1C, 2C, and 3C.
Liu et al. [164]	PCM/copper foam with helical liquid channels	Lowered battery temperature by > 30 K compared to natural convection.
Weng et al. [165]	Heat pipe embedded inPCM, utilizing forced and natural convection	Enhanced thermal management for improved heat dissipation.
Zhang et al. [166]	PCM and liquid cooling to control thermal runaway	Improved temperature uniformity, effectively contained thermal runaway in battery modules.
Hekmat and Molaeimanesh [167]	Water pipes in PCM sandwich structure	Significantly improved temperature uniformity for prismatic batteries.
Wuet al. [168]	PCM filling between cylindrical batteries with mini channel cold plate	Maintained stable battery temperatures, with mini channel cold plate enhancing thermal stability.
Akbarzadeh et al. [169]	Hybrid liquid/PCM cold plates in prismatic modules	Achieved up to 30% reduction in coolant pumping power, greatly enhanced temperature uniformity.

Cao et al. [170]	PCM-based hybrid cold plate with delayed cooling technique	Maintained temperature uniformity and minimized power consumption.
Hu et al. [171]	Passive-active hybrid cooling with controlled pump start-up time	Sufficient for low-rate heat dissipation; active cooling used only for extreme conditions, improving energy efficiency.
Mousavi et al. [172]	PCM with vertically oriented mini-channel cool plates for prismatic batteries	Reduced power consumption per cell by 68% at 3C discharge; reduced temperature differential by up to 33% with PCM plates.
Rao et al. [173]	PCM/mini channel hybrid system, evaluating flow rate, conduction, and melting point	Optimal PCM melting temperature at 308.15 K and conduction of 0.6 W/m·K; maximum temperature of 320.6 K, lower than the 335.4 K in PCM-only systems.

Table 3 presents a comprehensive summary of recent research advances in thermal management systems integrating convective cooling with phase change materials and thermal transfer conduits.

6.2 Advanced Materials for Battery Cooling: Nanomaterials and Graphene

The escalating demand for high-performance, safe, and durable batteries, particularly in electric vehicles (EVs) and energy storage systems, has intensified the need for effective battery thermal management systems (BTMS). Conventional cooling methods often fall short in addressing the complex thermal challenges posed by modern batteries. Advanced materials, notably nanomaterials and graphene, offer transformative solutions by leveraging their exceptional thermal properties.

6.2.1 Nanomaterials: Tailoring Thermal Properties for Enhanced Cooling

Nanomaterials, characterized by their nanoscale dimensions, exhibit unique physical and chemical properties that significantly enhance heat transfer. Their high surface area-to-volume ratio, quantum confinement effects, and tailored surface functionalities enable them to outperform traditional materials in BTMS applications.

Carbon Nanotubes (CNTs): High Thermal Conductivity Pathways:

Thermal Conductivity: CNTs, both single-walled (SWCNTs) and multi-walled (MWCNTs), possess exceptionally high thermal conductivity, exceeding 3,000 W/mK along their axial direction. This makes them ideal for creating efficient heat conduction pathways within BTMS.

Applications:

Heat Sinks and Cooling Plates: CNT-enhanced composites can be used to fabricate heat sinks and cooling plates with improved thermal conductivity, facilitating rapid heat dissipation.

Phase Change Materials (PCMs): Incorporating CNTs into PCMs enhances their thermal conductivity, accelerates heat absorption and release, and improves their overall thermal performance.

Thermal Interface Materials (TIMs): CNT-based TIMs provide efficient heat transfer between battery cells and cooling systems, minimizing thermal resistance.

Challenges:

Dispersion and alignment of CNTs within matrices are critical for achieving optimal thermal performance.

High production costs and scalability remain significant challenges.

Metallic Nanoparticles: Enhancing Convective Heat Transfer

Nanofluids: Metallic nanoparticles, such as Al_2O_3, CuO, and Ag, dispersed in base fluids, form nanofluids with enhanced thermal conductivity and convective heat transfer coefficients.

Mechanism: Nanoparticles increase the effective thermal conductivity of the fluid, promote turbulence, and enhance heat transfer at the fluid-solid interface.

Applications:

Liquid cooling systems: Nanofluids improve the efficiency of liquid cooling by enhancing heat removal from battery modules.

Microchannel and minichannel cooling: Nanofluids enhance the performance of microchannel and minichannel cooling systems, which are crucial for compact battery modules.

Considerations:

Stability and agglomeration of nanoparticles in the fluid are critical factors affecting long-term performance.

Potential for increased viscosity and pressure drop needs to be carefully evaluated.

Boron Nitride Nanotubes (BNNTs): Thermal Conductivity with Electrical Insulation

Dual Functionality: BNNTs offer high thermal conductivity (similar to CNTs) while providing electrical insulation, a crucial property for battery cooling applications.

Applications:

Electrically insulating thermal interface materials.

Thermally conductive insulating coatings for battery components.

Advantages:

Eliminates the risk of electrical short circuits, enhancing battery safety.

Enables the development of compact and efficient BTMS.

6.2.2 Graphene: The Ultimate Thermal Conductor

Graphene's exceptional in-plane thermal conductivity (over 5,000 W/mK) makes it a game-changer in battery thermal management. Its unique two-dimensional structure and strong carbon-carbon bonds contribute to its superior thermal properties.

Applications of Graphene in BTMS

Thermal Interface Materials (TIMs): Graphene-based TIMs provide ultra-high thermal conductivity, minimizing thermal resistance between battery cells and cooling systems.

Heat Spreaders and Cooling Films: Graphene sheets and films can be integrated into battery modules to create efficient heat spreaders, ensuring uniform temperature distribution.

Graphene-Enhanced PCMs: Incorporating graphene into PCMs significantly enhances their thermal conductivity and improves their ability to absorb and release heat.

Graphene-Based Nanofluids: Graphene-based nanofluids exhibit superior thermal conductivity and heat transfer capabilities compared to conventional coolants and metallic nanoparticle-based nanofluids.

Electrode and current collectors: Graphene can be added to the electrode or current collectors to improve the heat transfer properties of the battery itself.

Advantages of Graphene-Based BTMS

Ultra-High Thermal Conductivity: Enables rapid and efficient heat dissipation, preventing overheating and thermal runaway.

Lightweight and Flexible: Allows for the development of compact and flexible BTMS, suitable for various battery configurations.

Enhanced Thermal Stability: Improves the thermal stability of battery components and cooling systems.

Challenges and Future Directions

Production Costs: Large-scale production of high-quality graphene remains expensive.

Integration and Processing: Developing efficient methods for integrating graphene into existing battery designs is crucial.

Functionalization: Tailoring the surface properties of graphene to enhance its compatibility with other materials is essential.

Hybrid materials: Creating hybrid materials that combine graphene with other materials, to gain the high thermal conductivity, and reduce the overall cost.

7. Challenges and Future Directions

As the global transition toward decarbonization accelerates, the shift from fossil fuel-based transportation to green energy-powered electric vehicles (EVs) has increased the need for efficient thermal management of lithium-ion battery packs. Researchers have explored numerous techniques to enhance battery thermal management systems (BTMS) to improve EV performance. However, significant opportunities remain for further advancements in various aspects of BTMS, which are outlined below.

Air-cooling systems are widely adopted due to their simple construction, low operational cost, and ease of implementation. However, their effectiveness is limited by air's low thermal conductivity and specific heat capacity. To improve air cooling performance, innovative battery pack designs, optimized airflow passages, and external airflow arrangements must be considered. Enhancing the spatial layout of battery modules can also contribute to superior cooling efficiency.

On the other hand, liquid cooling is one of the most effective solutions for BTMS. However, further research is necessary to optimize its performance while balancing energy consumption, cost, and compatibility with modern EVs. Phase change materials (PCMs) offer several advantages, including reduced energy consumption, minimal volume fluctuations, lower noise levels, and high cooling rates. However, the cooling efficiency of PCMs diminishes during phase transitions, particularly when the battery's operating temperature surpasses the PCM's melting point due to its inherently low thermal conductivity.

To address this limitation, extensive research is needed to develop composite PCMs with superior thermal properties for long-term BTMS operation. The integration of phase change liquid cooling and heat pipe technology is another promising approach, but large-scale, long-term implementation still requires significant development. The use of nanofluid-based heat pipes could improve heat transfer efficiency and cost-effectiveness, particularly considering EVs' stringent requirements such as fast charging, variable loads, and multiple thermal conditions. Additionally, micro heat pipes (MHPs) present an opportunity for further research to develop more efficient cooling strategies.

Incorporating low-temperature preheating methods, such as internal self-heating mechanisms within battery cells, holds potential for next-generation intelligent BTMS. Immersion cooling using dielectric liquids and refrigerant-based cooling techniques also offer promising solutions. However, their large-scale adoption requires a thorough investigation of factors such as fluid properties, stability, material compatibility, and system longevity.

Recent advancements in hybrid cooling systems that integrate multiple established techniques have demonstrated significant potential for BTMS optimization. However, further research is essential to develop cost-effective implementations. Additionally, optimizing battery pack design and vehicle structure using advanced computational methods, including various optimization algorithms, is crucial for enhancing thermal management.

Future EVs must incorporate intelligent design strategies to maximize efficiency, improve control systems, minimize battery power consumption, optimize space utilization, and enhance subsystem integration within BTMS. This calls for extensive research and technological advancements in thermal management.

Machine learning (ML) tools offer a promising avenue for optimizing BTMS, facilitating the rapid development of digital twin models. However, further research is needed to refine these models for enhanced accuracy and reliability. Artificial neural networks (ANNs) provide multivariate analysis capabilities, high precision, and strong noise tolerance, making them valuable for optimizing parameters and designing more efficient BTMS. Nonetheless, extensive study is still required to fully realize their potential.

7.1 Current Gaps, Outlook, and Manufacturing Challenges.

7.1.1 Challenges

Several key challenges persist in the research and development of Battery Thermal Management Systems (BTMS). These include optimizing material selection, enhancing system safety and thermal dissipation, reducing overall weight and complexity, and integrating artificial intelligence (AI) and machine learning (ML) for improved predictive capabilities and monitoring. A comprehensive and customizable approach, incorporating both software and hardware advancements, is essential to meet specific thermal requirements [190]. The primary challenges in BTMS are outlined below:

Thermal Runaway and Safety: Maintaining battery temperatures within an optimal range is critical to preventing thermal runaway and associated safety risks. Despite progress in BTMS development, high-energy-density batteries still generate substantial heat, particularly during rapid charging and high-power operations, necessitating more effective thermal management strategies [190].

Electrode and Material Optimization: The chemical reactions within batteries occur at the electrodes, and reducing internal resistance can minimize heat generation while improving cell capacity and electrode longevity. However, excessively thin electrodes may compromise energy storage capabilities, and trade-offs exist between efficiency and increased manufacturing costs [158].

AI and ML for Predictive Thermal Management: While AI and ML have been employed to predict battery thermal behavior, selecting the most effective models remains a challenge. Although these technologies have reduced costs and accelerated material selection for BTMS, optimizing materials for high-performance systems operating under extreme thermal conditions remains an ongoing issue [190].

Weight, Volume, and Efficiency Trade-offs: Various BTMS approaches, such as liquid cooling, phase change materials (PCMs), and hybrid systems, add significant weight and bulk to battery packs, limiting their scalability for applications with space constraints, including electric vehicles (EVs) and aircraft. Additionally, the thermal conductivity of PCMs requires improvement to enhance heat dissipation under high loads. While air-cooling systems offer a lightweight and straightforward solution, they are often inadequate for managing substantial thermal loads [23,191,192,193].

Sustainability and Regulatory Compliance: Developing BTMS that adhere to sustainability regulations while maintaining economic feasibility remains a significant challenge. Ensuring compliance with environmental standards without compromising performance and affordability is crucial for widespread adoption [190].

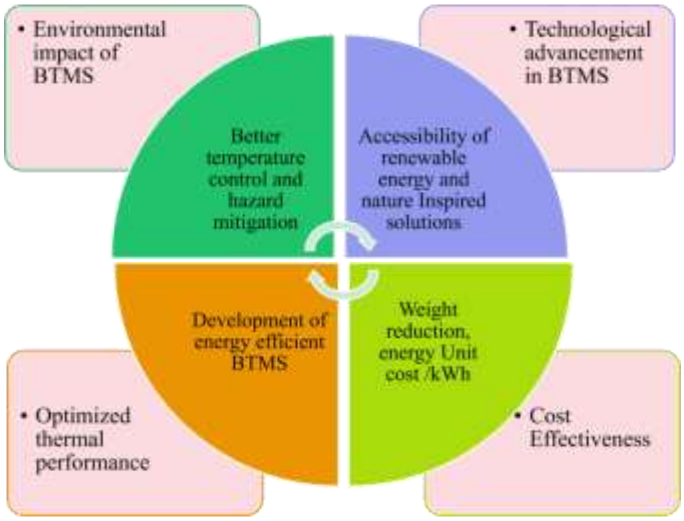


Figure 11: Sustainable thermal management development chart.

7.1.2 Opportunities

Despite these challenges, numerous opportunities exist for advancing BTMS technology, as highlighted below:

Early Detection and AI Integration: The incorporation of advanced temperature and pressure sensors, combined with AI-driven predictive algorithms, can enable real-time monitoring and early detection of potential safety hazards, thereby improving system reliability and operational efficiency [190].

Additive Manufacturing and 3D Printing: The integration of additive manufacturing with cutting-edge materials, such as graphene and other 2D nanomaterials, offers significant potential for enhancing BTMS performance. These advanced materials can improve heat transfer efficiency and overall thermal management capabilities [27,191,193].

Smart Battery Thermal Management: The development of self-adaptive, intelligent BTMS can lead to near-zero energy and liquid-free cooling solutions. Innovations such as metal-organic frameworks (MOFs) can enable dynamic heating and cooling based on environmental conditions, optimizing energy usage and thermal regulation [190].

Sustainability and Energy Efficiency: Moving beyond conventional cooling techniques, where excess heat is dissipated into the environment, future BTMS solutions should focus on sustainability. Advancements in heat exchange systems can help reduce energy consumption and emissions. Additionally, integrating thermoelectric generators into BTMS can convert waste heat into usable electricity, paving the way for innovative cogeneration systems [188].

Advanced Designs and Materials: The application of novel design structures, such as Triply Periodic Minimal Surface (TPMS) geometries and vibration-enhanced BTMS, offers promising improvements in thermal stability and energy efficiency. Furthermore, nanoengineered porous silica and flexible PCMs can enhance cooling performance and battery safety. Biomimetic designs, inspired by natural structures like leaf vein networks, can also improve heat dissipation efficiency and be tailored to different battery configurations for optimized performance [190].

Cost Considerations: While thermal performance has been extensively studied, cost implications are often overlooked. Recent simulation-based studies have shown that optimizing battery pack configurations, such as adjusting the spacing between cylindrical cells in a PCM-assisted system, can significantly reduce operational costs. Efficient battery arrangement can lower the electricity consumption needed to solidify PCM, making the system more cost-effective [190].

7.1.3 Patent Analysis and Technology Trends

Patent data analysis provides valuable insights into technological advancements in BTMS, guiding enterprise research and development efforts while informing technology life cycles. Evaluating patents helps assess the cost-effectiveness of different BTMS solutions across varying climatic conditions, offering practical applications for industry and policy decisions.

Yang and Shi categorized battery patents into three levels: cell, module, and pack. Their findings indicate that while cell-level technology is relatively mature, module- and pack-level innovations are still evolving due to increasing demand for larger, higher-performance batteries for EVs. Patent analysis also highlights key countries and industry leaders driving BTMS innovation, providing crucial intelligence for research collaborations and technological partnerships [195].

Additionally, Spreafico et al. have explored the role of patent analysis in supporting Life Cycle Assessment (LCA). They proposed a prospective LCA framework that evaluates the environmental sustainability of emerging BTMS technologies before they reach commercial viability. However, conducting a comprehensive patent analysis is beyond the scope of this review [196,197].

8. Conclusion

Battery Thermal Management Systems (BTMS) are integral to enhancing the safety, efficiency, and longevity of lithium-ion batteries, particularly in electric vehicles (EVs). Traditional cooling methods, including air cooling, liquid cooling, phase change materials (PCMs), and heat pipes, each offer unique advantages but also present limitations in terms of energy consumption, scalability, and thermal regulation. As EV technology advances, the demand for more effective and sustainable thermal management solutions continues to grow.

Recent advancements in BTMS focus on hybrid cooling strategies, nanomaterial integration, AI-driven predictive modeling, and sustainable design approaches. The incorporation of advanced materials such as graphene, nanofluids, and metal-organic frameworks (MOFs), along with smart self-regulating thermal management, has demonstrated significant potential in optimizing heat dissipation and improving battery reliability. AI-powered control systems further enhance efficiency by enabling real-time monitoring, adaptive cooling, and early fault detection, reducing thermal runaway risks.

Future research should prioritize cost-effective large-scale implementation, energy-efficient hybrid cooling solutions, and environmentally friendly cooling strategies. By integrating machine learning, additive manufacturing, and biomimetic designs, next-generation BTMS can achieve superior thermal performance while maintaining sustainability. As the global transition toward green energy accelerates, continuous innovation in BTMS will play a pivotal role in improving EV adoption, battery life cycles, and overall energy storage solutions.

References

[1] X. Zhang, et al., "A review on thermal management of lithium-ion batteries for electric vehicles," *Energy*, vol. 238, p. 121652, 2022.
[2] J. Hong, et al., "Investigation on overcharge-caused thermal runaway of lithium-ion batteries in real-world electric vehicles," *Applied Energy*, vol. 321, p. 119229, 2022.
[3] J. Luo, et al., "Battery thermal management systems (BTMs) based on phase change material (PCM): a comprehensive review," *Chemical Engineering Journal*, vol. 430, p. 132741, 2022.
[4] A. Olabi, et al., "Battery thermal management systems: recent progress and challenges," *International Journal of Thermofluids*, vol. 15, p. 100171, 2022.
[5] A. Li, et al., "Machine learning assisted advanced battery thermal management system: a state-of-the-art review," *Journal of Energy Storage*, vol. 60, p. 106688, 2023.
[6] F. Bahiraei, et al., "A pseudo 3D electrochemical-thermal modeling and analysis of a lithium-ion battery for electric vehicle thermal management applications," *Applied Thermal Engineering*, vol. 125, pp. 904–918, 2017.
[7] H. Fayaz, et al., "Optimization of thermal and structural design in lithium-ion batteries to obtain energy efficient battery thermal management system (BTMS): a critical review," *Archives of Computational Methods in Engineering*, vol. 29, no. 1, pp. 129–194, 2022.
[8] M. Lu, et al., "Research progress on power battery cooling technology for electric vehicles," *Journal of Energy Storage*, vol. 27, p. 101155, 2020.
[9] K.M. Tan, et al., "Empowering smart grid: a comprehensive review of energy storage technology and application with renewable energy integration," *Journal of Energy Storage*, vol. 39, p. 102591, 2021.
[10] Y. Tian, et al., "Promises and challenges of next-generation 'Beyond Li-ion' batteries for electric vehicles and grid decarbonization," *Chemical Reviews*, vol. 121, no. 3, pp. 1623–1669, 2021.
[11] S. Ma, et al., "Phase change materials for thermal management of lithium-ion batteries: state-of-the-art and future directions," *Energy Materials*, vol. 28, pp. 47–72, 2021.
[12] M. N. A. Rahman, et al., "Thermal management strategies for Li-ion battery systems in electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109254, 2019.
[13] Y. Yang, et al., "Solar energy powered battery thermal management system for electric vehicles," *Renewable Energy*, vol. 138, pp. 999–1011, 2019.
[14] D. Zhang, et al., "Design of renewable energy-powered battery thermal management system for electric vehicle," *Energy*, vol. 189, p. 116469, 2019.
[15] UN Sustainable Development Goals, *United Nations*, 2020. [Online]. Available: https://sdgs.un.org/goals
[16] J. Xie, et al., "Techno-economic analysis of sustainable energy storage solutions for electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 106, pp. 130–145, 2019.
[17] S. Lee, et al., "Photovoltaic powered thermal management of lithium-ion batteries," *Energy*, vol. 201, p. 117563, 2020.
[18] H. Huang, et al., "Hybrid energy storage systems with renewable energy integration for electric vehicle applications," *Energy*, vol. 179, pp. 66–75, 2019.
[19] H. He, et al., "Thermal management of lithium-ion batteries: a review of techniques and developments," *Energy Storage Materials*, vol. 17, pp. 43–59, 2019.
[20] Z. Li, et al., "AI-assisted optimization of battery thermal management systems," *Energy Science & Engineering*, vol. 8, pp. 1189–1203, 2020.
[21] S. Al-Hallaj and J. R. Selman, "Thermal management of Li-ion batteries with phase change materials," *Journal of Power Sources*, vol. 90, no. 1, pp. 1–8, 2000.
[22] Z. Rao, S. Wang, and M. Wu, "A review of power battery thermal energy management," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3584–3602, 2018.
[23] G. Zhang, L. Cao, and S. Ge, "Environmental impacts of battery cooling systems in electric vehicles," *Journal of Cleaner Production*, vol. 258, p. 120753, 2020.
[24] Tesla, Inc., "Battery thermal management in Tesla vehicles," *Tesla Engineering Blog*, 2020.
[25] BMW Group, "Liquid cooling systems in BMW i3," *BMW Technical Report*, 2019.
[26] Nissan Motor Corporation, "Air cooling in Nissan Leaf," *Nissan Technical Review*, 2017.
[27] K. Chen and J. W. Evans, "Heat pipe cooling for Li-ion batteries," *Applied Thermal Engineering*, vol. 100, pp. 882–890, 2016.
[28] Q. Wang and B. Jiang, "A comparative analysis of battery cooling methods," *Energy Conversion and Management*, vol. 195, pp. 346–356, 2019.
[29] General Motors, *Chevy Bolt Recall Report*, 2021.
[30] K. Smith and C. Y. Wang, "Power and thermal characterization of Li-ion batteries," *Journal of the Electrochemical Society*, vol. 154, no. 2, pp. A1–A7, 2007.
[31] L. H. Saw, Y. Ye, and A. A. O. Tay, "Integration issues of lithium-ion battery into electric vehicles battery pack," *Journal of Cleaner Production*, vol. 113, pp. 1032–1045, 2016.
[32] J. Jaguemont, N. Omar, and J. Van Mierlo, "Phase-change materials for thermal management of Li-ion batteries," *Applied Energy*, vol. 213, pp. 509–519, 2018.
[33] A. A. Pesaran, "Battery thermal management in EVs and HEVs: Issues and solutions," *Advanced Automotive Battery Conference*, 2002.
[34] F. Jaliliantabar, Thermal conductivity prediction of nano enhanced phase change materials: a comparative machine learning approach, J. Energy Storage 46 (2022).
[35] J. Wen, Q. Zou, Y. Wei, Physics-driven machine learning model on temperature and time-dependent deformation in lithium metal and its finite element implementation, J. Mech. Phys. Solids 153 (2021).
[36] Hu Rehman, et al., Data analysis of a monitored building using machine learning and optimization of integrated photovoltaic panel, battery and electric vehicles in a Central European climatic condition, Energy Convers. Manag. (2020) 221.
[37] S. Su, et al., An adaptive boosting charging strategy optimization based on thermoelectric-aging model, surrogates and multi-objective optimization, Appl. Energy 312 (2022).

[38] X. Lai, et al., Mechanism, modeling, detection, and prevention of the internal short circuit in lithium-ion batteries: recent advances and perspectives, Energy Storage Mater. 35 (2021) 470–499.
[39] T. Gao, W. Lu, Machine learning toward advanced energy storage devices and systems, iScience 24 (1) (2021) 101936.
[40] K.-K. Xu, H.-X. Li, Z. Liu, ISOMAP-based spatiotemporal modeling for lithium-ion battery thermal process, IEEE Trans. Ind. Inform. 14 (2) (2018) 569–577.
[41] X. Hu, et al., Research directions for next-generation battery management solutions in automotive applications, Renew. Sustain. Energy Rev. 152 (2021).
[42] M. Arrinda, et al., Surrogate model of the optimum global battery pack thermal management system control, Energies 15 (5) (2022).
[43] X. Lin, et al., Optimization investigation on air phase change material based battery thermal management system, Energy Technol. 9 (7) (2021).
[44] I. Mokashi, et al., Nusselt number analysis from a battery pack cooled by different fluids and multiple back-propagation modelling using feed-forward networks, Int.J. Therm. Sci. 161 (2021).
[45] S. Su, et al., Multi-objective design optimization of battery thermal management system for electric vehicles, Appl. Therm. Eng. 196 (2021).
[46] Y. Li, et al., Safety modeling and protection for lithium-ion batteries based on artificial neural networks method under mechanical abuse, Sci. China Technol. Sci. 64 (11) (2021) 2373–2388.
[47] J. Park, Y. Kim, Supervised-learning-based optimal thermal management in an electric vehicle, IEEE Access 8 (2020) 1290–1302.
[48] M. Mesgarpour, et al., An evaluation of the thermal behaviour of a lithium-ion battery pack with a combination of pattern-based artificial neural networks (PBANN) and numerical simulation, J. Energy Storage 47 (2022).
[49] K. Boonma, et al., Prediction of battery thermal behaviour in the presence of a constructal theory-based heat pipe (CBHP): a multiphysics model and pattern- based machine learning approach, J. Energy Storage 48 (2022).
[50] O. Kalkan, et al., Prediction of experimental thermal performance of new designed cold plate for electric vehicles' Li-ion pouch-type battery with artificial neural network, J. Energy Storage 48 (2022).
[51] S. Zhu, et al., Data-driven analysis on thermal effects and temperature changes of lithium-ion battery, J. Power Sources 482 (2021).
[52] F. Feng, et al., Co-estimation of lithium-ion battery state of charge and state of temperature based on a hybrid electrochemical-thermal-neural-network model,J. Power Sources 455 (2020).
[53] S. Arora, W. Shen, A. Kapoor, Neural network based computational model for estimation of heat generation in LiFePO 4 pouch cells of different nominal capacities, Comput. Chem. Eng. 101 (2017) 81–94.
[54] A. Shahsavar, et al., The entropy generation analysis of the influence of using fins with tip clearance on the thermal management of the batteries with phase change material: application a new gradient-based ensemble machine learning approach, Eng. Anal. Bound. Elem. 140 (2022) 432–446.
[55] Y. Shi, et al., Optimization of air-cooling technology for LiFePO4 battery pack based on deep learning, J. Power Sources 497 (2021).
[56] R. Yang, et al., Extreme learning machine-based thermal model for lithium-ion batteries of electric vehicles under external short circuit, Engineering 7 (3) (2021) 395–405.
[57] K. Xu, et al., A two-scale manifold learning method for spatiotemporal modeling of lithium-ion battery thermal process, Nonlinear Dyn. (2022).
[58] T. Duraisamy, D. Kaliyaperumal, Machine learning-based optimal cell balancing mechanism for electric vehicle battery management system, IEEE Access 9 (2021) 132846–132861.
[59] S. Chen, et al., A comprehensive analysis and optimization process for an integrated liquid cooling plate for a prismatic lithium-ion battery module, Appl. Therm. Eng. 156 (2019) 324–339.
[60] S. Cai, et al., Physics-informed neural networks (PINNs) for fluid mechanics: a review, Acta Mech. Sin. 37 (12) (2022) 1727–1738.
[61] B. Farhadi, et al., Machine learning for fast development of advanced energy materials, Materials 1 (3) (2023) 100025.
[62] V. Kannan, A. Fisher, E. Birgersson, Monte Carlo assisted sensitivity analysis of a Li-ion battery with a phase change material, J. Energy Storage 35 (2021).
[63] J. Kleiner, et al., Real-time core temperature prediction of prismatic automotive lithium-ion battery cells based on artificial neural networks, J. Energy Storage 39 (2021).
[64] F. Jaliliantabar, R. Mamat, S. Kumarasamy, Prediction of lithium-ion battery temperature in different operating conditions equipped with passive battery thermal management system by artificial neural networks, Mater. Today.: Proc. 48 (2022) 1796–1804.
[65] M.K. Tran, et al., Python-based scikit-learn machine learning models for thermal and electrical performance prediction of high-capacity lithium-ion battery, Int. J. Energy Res. 46 (2) (2022) 786–794.
[66] L. Yuan, et al., Cell temperature prediction in the refrigerant direct cooling thermal management system using artificial neural network, Appl. Therm. Eng. 254 (2024) 123852.
[67] K.R. Sagar, et al., The Impact of Training Algorithms and Transfer Functions on the Accuracy of Neural Network-Based Temperature Prediction of 3S4P Battery Module. International Conference on Advances in Energy Research., Springer, 2023.
[68] K.S. Garud, et al., Artificial neural network modeling to predict thermal and electrical performances of batteries with direct oil cooling, Batteries 9 (11) (2023) 559.
[69] N. Sukkam, et al., Machine learning prediction of a battery's thermal-related health factor in a battery electric vehicle using real-world driving data, Information 15 (9) (2024) 553
[70] A. Al Miaari, H.M. Ali, Batteries temperature prediction and thermal management using machine learning: an overview, Energy Rep. 10 (2023) 2277–2305.
[71] M. Wang, et al., Internal temperature prediction of ternary polymer lithium-ion battery pack based on CNN and virtual thermal sensor technology, Int. J. Energy Res. 45 (9) (2021) 13681–13691.
[72] H. Li, et al., Multi-field interpretation of internal short circuit and thermal runaway behavior for lithium-ion batteries under mechanical abuse, Energy 263 (2023) 126027.
[73] C. Zhang, et al., Coupled mechanical-electrical-thermal modeling for short-circuit prediction in a lithium-ion cell under mechanical abuse, J. Power Sources 290 (2015) 102–113.
[74] H. Li, et al., Coupled mechanical–electrochemical–thermal study on the short- circuit mechanism of lithium-ion batteries under mechanical abuse,J. Electrochem. Soc. 167 (12) (2020) 120501.
[75] S.-Y. Park, et al., Observation and modeling of the thermal runaway of high- capacity pouch cells due to an internal short induced by an indenter, J. Energy Storage 72 (2023) 108518.
[76] C. Zhang, et al., A representative-sandwich model for simultaneously coupled mechanical-electrical-thermal simulation of a lithium-ion cell under quasi-static indentation tests, J. Power Sources 298 (2015) 309–321.
[77] Z. Chai, et al., Experimental analysis and safety assessment of thermal runaway behavior in lithium iron phosphate batteries under mechanical abuse, Sci. Rep. 14(1) (2024) 8673.
[78] A. Karmakar, et al., State-of-charge implications of thermal runaway in li-ion cells and modules, J. Electrochem. Soc. 171 (1) (2024) 010529.
[79] Y. Wang, et al., Parameter sensitivity analysis of a multi-physics coupling aging model of lithium-ion batteries, Electrochim. Acta 477 (2024) 143811.
[80] B. Liu, et al., Safety issues and mechanisms of lithium-ion battery cell upon mechanical abusive loading: a review, Energy Storage Mater. 24 (2020) 85–112.
[81] C. Liu, L. Liu, Optimal design of Li-ion batteries through multi-physics modeling and multi-objective optimization, J. Electrochem. Soc. 164 (11) (2017) E3254.
[82] K. Suresh, An Artificially Intelligent Battery Management System. 2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), IEEE, 2024.
[83] H. Cheng, S. Jung, Y.-B. Kim, Battery thermal management system optimization using Deep reinforced learning algorithm, Appl. Therm. Eng. 236 (2024) 121759.
[84] Y. Yi, et al., Digital twin-long short-term memory (LSTM) neural network based real-time temperature prediction and degradation model analysis for lithium-ion battery, J. Energy Storage 64 (2023) 107203.
[85] A.G. Olabi, et al., Artificial neural network driven prognosis and estimation of Lithium-Ion battery states: current insights and future perspectives, Ain Shams Eng. J. 15 (2) (2024) 102429.
[86] S. Ahmad, et al., Modeling liquid immersion-cooling battery thermal management system and optimization via machine learning, Int. Commun. Heat. Mass Transf. 158 (2024) 107835.
[87] S.A. Khan, et al., Advancements in battery thermal management system for fast charging/discharging applications, Energy Storage Mater. 65 (2024) 103144.
[88] X. Tang, et al., Performance analysis on liquid-cooled battery thermal management for electric vehicles based on machine learning, J. Power Sources 494 (2021) 229727.
[89] S.A. Khan, et al., Design of a new optimized U-shaped lightweight liquid-cooled battery thermal management system for electric vehicles: a machine learning approach, Int. Commun. Heat. Mass Transf. 136 (2022) 106209.
[90] S. Qi, et al., Advanced deep learning techniques for battery thermal management in new energy vehicles, Energies 17 (16) (2024) 4132.
[91] A. Afzal, M.K. Ramis, Multi-objective optimization of thermal performance in battery system using genetic and particle swarm algorithm combined with fuzzy logics, J. Energy Storage 32 (2020) 101815.
[92] Hannan, M.A., et al. Lithium Ion Battery Thermal Management System Using Optimized Fuzzy Controller. in 2019 IEEE Industry Applications Society Annual Meeting. 2019.
[93] M. Abdullah, et al., Electric vehicle battery temperature control using fuzzy logic, Autom. Control Comput. Sci. 58 (3) (2024) 237–251.
[94] W. Li, et al., Optimization for liquid cooling cylindrical battery thermal management system based on gaussian process model, J. Therm. Sci. Eng. Appl. 13 (2) (2020).
[95] Sung, N., et al. Cooling-Guided Diffusion Model for Battery Cell Arrangement. in ASME 2024 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2024.
[96] Fan, Z., et al., A novel battery thermal management system based on P type triply periodic minimal surface. 2022. 194: p. 123090.
[97] S. Ali, J. Shin, In-Depth characterization of laser-welded aluminum-and-copper dissimilar joint for electric vehicle battery connections, Materials 15 (21) (2022) 7463.
[98] Zuo, S., et al., Performance analysis and improvement of lithium-ion battery thermal management system using mini-channel cold plate under vibration environment. 2022. 193: p. 122956.
[99] Joshy, N., et al., Experimental investigation of the effect of vibration on phase change material (PCM) based battery thermal management system. 2020. 450: p. 227717.
[100] Huang, Q., et al., Pouch Lithium Battery with a Passive Thermal Management System Using Form-Stable and Flexible Composite Phase Change Materials. 2021. 4: p. 1978-1992.
[101] Xiao, C., et al., Ultrareliable Composite Phase Change Material for Battery Thermal Management Derived from a Rationally Designed Phase Changeable and Hydrophobic Polymer Skeleton. 2021. **4**: p. 3832-3841.
[102] Nofal, M., et al., Thermal management of lithium-ion battery cells using 3D printed phase change composites. 2020. **171**: p. 115126.
[103] Guo, H., et al., Highly Thermally Conductive 3D Printed Graphene Filled Polymer Composites for Scalable Thermal Management Applications. 2021. **15**: p. 6917- 6928.
[104] EL IDI, M.M.M., et al., Hybrid cooling based battery thermal management using composite phase change materials and forced convection. 2021. **41**: p. 102946.
[105] Li, P., et al., Heat transfer enhancement, entropy generation and temperature uniformity analyses of shark-skin bionic modified microchannel heat sink. 2020. **146**: p. 118846.
[106] L. An, et al., Tailoring thermal insulation architectures from additive manufacturing, Nature Communications 13 (1) (2022) 4309.
[107] N. Hamid, et al., Challenges in thermal management of lithium-ion batteries using phase change nanocomposite materials: a review, J. Energy Storage 100 (2024) 113731.
[108] G. Liao, et al., Thermal performance of lithium-ion battery thermal management system based on nanofluid, Appl. Therm. Eng. 216 (2022) 118997.
[109] A.G. Olabi, et al., Battery thermal management systems: recent progress and challenges, Int. J. Thermofluids 15 (2022) 100171.
[110] H.M. Maghrabie, et al., Applications of Nanofluids in Cooling of Electronic Components, in: A.-G. Olabi (Ed.), Encyclopedia of Smart Materials, Elsevier, Oxford., 2022, pp. 310–318.
[111] H. Xie, et al., Discussion on the thermal conductivity enhancement of nanofluids, Nanoscale Res. Lett. 6 (1) (2011) 124.
[112] F. Wu, Z. Rao, The lattice Boltzmann investigation of natural convection for nanofluid based battery thermal management, Appl. Therm. Eng. 115 (2017) 659–669.
[113] P. Kumar, et al., Critical review on battery thermal management and role of nanomaterial in heat transfer enhancement for electrical vehicle application,
J. Energy Storage 32 (2020) 102003.
[114] P.B. Maheshwary, et al., Role of nanoparticle shape in enhancing the thermal conductivity of nanofluids, Mater. Today.: Proc. 28 (2020) 873–878.
[115] M. Tousi, et al., Numerical study of novel liquid-cooled thermal management system for cylindrical Li-ion battery packs under high discharge rate based on AgO nanofluid and copper sheath, J. Energy Storage 41 (2021) 102910.
[116] B. Bakthavatchalam, et al., Comprehensive study on nanofluid and ionanofluid for heat transfer enhancement: a review on current and future

perspective, J. Mol. Liq. 305 (2020) 112787.
[117] S. Wiriyasart, et al., Thermal management system with nanofluids for electric vehicle battery cooling modules, Case Stud. Therm. Eng. 18 (2020) 100583.
[118] T.I.C. Buidin, F. Mariasiu, Battery thermal management systems: current status and design approach of cooling technologies, Energies 14 (16) (2021) 4879.
[119] M.A. Abdelkareem, et al., Heat pipe-based waste heat recovery systems: Background and applications, Therm. Sci. Eng. Prog. 29 (2022) 101221.
[120] M.P. Narayanasamy, et al., Heat transfer analysis of looped micro heat pipes with graphene oxide nanofluid for Li-ion battery, Therm. Sci. 25 (1 Part A) (2021) 395–405.
[121] Z. Zhou, et al., Performance evaluation of hybrid oscillating heat pipe with carbon nanotube nanofluids for electric vehicle battery cooling, Appl. Therm. Eng. 196 (2021) 117300.
[122] M. Chen, J. Li, Nanofluid-based pulsating heat pipe for thermal management of lithium-ion batteries for electric vehicles, J. Energy Storage 32 (2020) 101715.
[123] F. Nasir, et al., Nanofluid-filled heat pipes in managing the temperature of EV lithium-ion batteries. Journal of Physics: Conference Series, IOP Publishing, 2019.
[124] Z. Said, et al., Nano-enhanced phase change materials: Fundamentals and applications, Prog. Energy Combust. Sci. 104 (2024) 101162.
[125] An, L., et al., Nanoengineering Porous Silica for Thermal Management. 2022. **5**: p. 2655-2663.
[126] Wu, T., et al., Effect Analysis on Thermal Management of Power Batteries Utilizing a Form-Stable Silicone Grease/Composite Phase Change Material. 2021. **4**: p. 6233-6244.
[127] J. Xu, et al., Near-zero-energy smart battery thermal management enabled by sorption energy harvesting from air, ACS Cent. Sci. 6 (9) (2020) 1542–1554.
[128] Wang, F., et al., Sorption Energy Harvesting from Air for Smart Battery Thermal Management. 2020. **6**: p. 1479-1481.
[129] Joula, M., et al., Hybrid Battery Thermal Management System with NiTi SMA and Phase Change Material (PCM) for Li-ion Batteries. 2022. **15**: p. 4403.
[130] Alnaqi, A.A. and Numerical analysis of pressure drop and heat transfer of a Non- Newtonian nanofluids in a Li-ion battery thermal management system (BTMS) using bionic geometries. 2022. **45**: p. 103670.
[131] Liu, F., et al., Optimal Design of Liquid Cooling Structure with Bionic Leaf Vein Branch Channel for Power Battery. 2022.
[132] Wang, J., et al., Numerical optimization of the cooling effect of the bionic spider- web channel cold plate on a pouch lithium-ion battery. 2021. **26**: p. 101124.
[133] Yang, W., et al., Thermal performance of honeycomb-like battery thermal management system with bionic liquid mini-channel and phase change materials for cylindrical lithium-ion battery. 2021. **188**: p. 116649.
[134] Li, B., et al., Study on battery thermal management of autonomous underwater vehicle by bionic wave channels with liquid cooling. 2021. **45**: p. 13269-13283.
[135] Yang, W., et al., Thermal performance of axial air cooling system with bionic surface structure for cylindrical lithium-ion battery module. 2020. **161**: p. 120307.
[136] Wang, Z., et al., Effect of wall roughness by the bionic structure of dragonfly wing on microfluid flow and heat transfer characteristics. 2021. **173**: p. 121201.
[137] Xu, J., et al., The enhanced cooling effect of water mist with additives on inhibiting lithium ion battery thermal runaway. 2022. **77**: p. 104784.
[138] V. Dimatteo, et al., Experimental investigation on the effect of spot diameter on continuous-wave laser welding of copper and aluminum thin sheets for battery manufacturing, Opt. Laser Technol. 145 (2022) 107495.
[139] Xu, J., et al., Experimental study of the cooling effect of water mist on 18650 lithium-ion battery at different initial temperatures. 2022. **157**: p. 156-166.
[140] Saw, L.H., et al., Novel thermal management system using mist cooling for lithium-ion battery packs. 2018. **223**: p. 146-158.
[141] Yuqi, H., et al., Numerical Study on the Use of Emergency Cooling During the Process of Lithium-Ion Battery Thermal Runaway. 2022. **19**.
[142] Zhang, L., et al., Experimental investigation on intermittent spray cooling and toxic hazards of lithium-ion battery thermal runaway. 2022. **252**: p. 115091.
[143] Wang, W., et al., Suppression behavior of water mist containing compound additives on lithium-ion batteries fire. 2022. **161**: p. 476-487.
[144] Wu, T., et al., Research on spray cooling performance based on battery thermal management. 2022. **46**: p. 8977-8988.
[145] L. Kong, et al., Li-ion battery fire hazards and safety strategies, Energies 11 (9) (2018) 2191.
[146] A. Bo¨rger, J. Mertens, H. Wenzl, Thermal runaway and thermal runaway propagation in batteries: what do we talk about? J. Energy Storage 24 (2019) 100649.
[147] J. Zhang, et al., An overview on thermal safety issues of lithium-ion batteries for electric vehicle application, IEEE Access 6 (2018) 23848–23863.
[148] F. Takahashi, Correction to: fire blanket and intumescent coating materials for failure resistance, MRS Bull. 46 (7) (2021), p. 642-642.
[149] Appleberry, M.C., et al., Avoiding thermal runaway in lithium-ion batteries using ultrasound detection of early failure mechanisms. 2022. **535**: p. 231423.
[150] M.A. Abdelkareem, et al., Environmental aspects of batteries, Sustain. Horiz. 8 (2023) 100074.
[151] S.S. Rawat, R. Kumar, Techno-economic analysis of cooling technologies used in electric vehicle battery thermal management: a review, J. Energy Storage 103 (2024) 114135.
[152] B.R. David, et al., Comparative environmental life cycle assessment of conventional energy storage system and innovative thermal energy storage system, Int. J. Thermofluids 12 (2021) 100116.
[153] M. Bernagozzi, et al., Performance of an environmentally friendly alternative fluid in a loop heat pipe-based battery thermal management system, Energies 14(22) (2021) 7738.
[154] S.E. Afia, et al., Energy sources and battery thermal energy management technologies for electrical vehicles: a technical comprehensive review, Energies 17 (22) (2024) 5634.
[155] M. Falcone, et al., Life cycle assessment of a lithium-ion battery pack unit made of cylindrical cells, Batteries 8 (8) (2022) 76.
[156] M. Chen, et al., Research progress of enhancing battery safety with phase change materials, Renew. Sustain. Energy Rev. 189 (2024) 113921.
[157] M.S.H. Lipu, et al., Battery management, key technologies, methods, issues, and future trends of electric vehicles: a pathway toward achieving sustainable development goals, Batteries 8 (9) (2022) 119.
[158] G. Rasool, et al., Recent advancements in battery thermal management system (BTMS): a review of performance enhancement techniques with an emphasis on nano-enhanced phase change materials, Heliyon (2024).
[159] S. Lei, S. Xin, S. Liu, Separate and integrated thermal management solutions for electric vehicles: a review, J. Power Sources 550 (2022) 232133.
[160] O. Teichert, F. Müller, M. Lienkamp, Techno-economic design of battery thermal management systems in different climates, J. Energy Storage 48 (2022) 103832.
[161] S. Yan, X. Cong, L. Zhao, Optimization Design Study of Thermal Management System for Lithiumion Batteries. 2024 6th International Conference on Electronic Engineering and Informatics (EEI), IEEE, 2024.
[162] Y.M. Alkhulaifi, N.A. Qasem, S.M. Zubair, Exergoeconomic assessment of the ejector-based battery thermal management system for electric and hybrid-electric vehicles, Energy 245 (2022) 123252.
[163] Yang H, Li M, Wang Z, Ma B. A compact and lightweight hybrid liquid cooling system coupling with Z-type cold plates and PCM composite for battery thermal management. Energy 2023;263(Jan). https://doi.org/10.1016/j. energy.2022.126026.
[164] Liu H, Ahmad S, Shi Y, Zhao J. A parametric study of a hybrid battery thermal management system that couples PCM/copper foam composite with helical liquid channel cooling. Energy 2021;231(Sep). https://doi.org/10.1016/j.energy.2021.120869.
[165] Weng J, Ouyang D, Yang X, Chen M, Zhang G, Wang J. Experimental study on thermal behavior of PCM-module coupled with various cooling strategies under different temperatures and protocols. Appl Therm Eng 2021;197(Oct). https:// doi.org/10.1016/j.applthermaleng.2021.117376.
[166] Zhang W, Liang Z, Yin X, Ling G. Avoiding thermal runaway propagation of lithium-ion battery modules by using hybrid phase change material and liquid cooling. Appl Therm Eng 2021;184(Feb). https://doi.org/10.1016/j.applthermaleng.2020.116380.
[167] Hekmat S, Molaeimanesh GR. Hybrid thermal management of a Li-ion battery module with phase change material and cooling water pipes: an experimental investigation. Appl Therm Eng 2020;166(Feb). https://doi.org/10.1016/j. applthermaleng.2019.114759.
[168] Wu X, Zhu Z, Zhang H, Xu S, Fang Y, Yan Z. Structural optimization of light-weight battery module based on hybrid liquid cooling with high latent heat PCM. Int J Heat Mass Tran 2020;163(Dec). https://doi.org/10.1016/j.ijheatmasstransfer.2020.120495.
[169] Akbarzadeh M, et al. A novel liquid cooling plate concept for thermal management of lithium-ion batteries in electric vehicles. Energy Convers Manag 2021;231(Mar). https://doi.org/10.1016/j.enconman.2021.113862.
[170] Cao J, Feng J, Fang X, Ling Z, Zhang Z. A delayed cooling system coupling composite phase change material and nano phase change material emulsion. Appl Therm Eng 2021;191(Jun). https://doi.org/10.1016/j.applthermaleng.2021.116888.
[171] Hu S, Wang S, Ma C, Li S, Liu X, Zhang Y. A hybrid cooling method with low energy consumption for lithium-ion battery under extreme conditions. Energy Convers Manag 2022;266(Aug). https://doi.org/10.1016/j.enconman.2022.115831.
[172] Mousavi S, Zadehkabir A, Siavashi M, Yang X. An improved hybrid thermal management system for prismatic Li-ion batteries integrated with mini-channel and phase change materials. Appl Energy 2023;334(Mar). https://doi.org/ 10.1016/j.apenergy.2023.120643.
[173] Rao Z, Wang Q, Huang C. Investigation of the thermal performance of phase change material/mini-channel coupled battery thermal management system. Appl Energy Feb. 2016;164:659–69. https://doi.org/10.1016/j.apenergy.2015.12.021.
[174] Ling Y, She X, Zhang X, Chen T, Lin X, Feng J. A PCM-based thermal management system combining three-dimensional pulsating heat pipe with forced-air cooling. Appl Therm Eng 2022;213(Aug). https://doi.org/10.1016/j.applthermaleng.2022.118732.
[175] Sharma DK, Prabhakar A. A review on air cooled and air centric hybrid thermal management techniques for Li-ion battery packs in electric vehicles. J Energy Storage Sep. 01, 2021;41. https://doi.org/10.1016/j.est.2021.102885. Elsevier Ltd.
[176] Dan D, Yao C, Zhang Y, Zhang H, Zeng Z, Xu X. Dynamic thermal behavior of micro heat pipe array-air cooling battery thermal management system based on thermal network model. Appl Therm Eng 2019;162(Nov). https://doi.org/10.1016/j.applthermaleng.2019.114183.
[177] Ling Z, Wang F, Fang X, Gao X, Zhang Z. A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling. Appl Energy Jun. 2015;148:403–9. https://doi.org/10.1016/j. apenergy.2015.03.080.
[178] Situ W, et al. A thermal management system for rectangular LiFePO4 battery module using novel double copper mesh-enhanced phase change material plates. Energy 2017;141:613–23. https://doi.org/10.1016/j.energy.2017.09.083.
[179] Wu W, et al. An experimental study of thermal management system using copper mesh-enhanced composite phase change materials for power battery pack. Energy Oct. 2016;113:909–16. https://doi.org/10.1016/j.energy.2016.07.119.
[180] Xie Y, et al. Experimental and numerical investigation on integrated thermal management for lithium-ion battery pack with composite phase change

materials. Energy Convers Manag Dec. 2017;154:562–75. https://doi.org/10.1016/j. enconman.2017.11.046.
[181] Zhao R, Gu J, Liu J. Optimization of a phase change material based internal cooling system for cylindrical Li-ion battery pack and a hybrid cooling design. Energy 2017;135:811–22. https://doi.org/10.1016/j.energy.2017.06.168.

[182] Mehrabi-Kermani M, Houshfar E, Ashjaee M. A novel hybrid thermal management for Li-ion batteries using phase change materials embedded in copper foams combined with forced-air convection. Int J Therm Sci Jul. 2019; 141:47–61. https://doi.org/10.1016/j.ijthermalsci.2019.03.026.
[183] Qin P, Liao M, Zhang D, Liu Y, Sun J, Wang Q. Experimental and numerical study on a novel hybrid battery thermal management system integrated forced-air convection and phase change material. Energy Convers Manag Sep. 2019;195: 1371–81. https://doi.org/10.1016/j.enconman.2019.05.084.
[184] Safdari M, Ahmadi R, Sadeghzadeh S. Numerical investigation on PCM encapsulation shape used in the passive-active battery thermal management. Energy 2020;193(Feb). https://doi.org/10.1016/j.energy.2019.116840.
[185] Bamdezh MA, Molaeimanesh GR. Impact of system structure on the performance of a hybrid thermal management system for a Li-ion battery module. J Power Sources May 2020;457. https://doi.org/10.1016/j.jpowsour.2020.227993.
[186] C. Huber, R. Kuhn, Thermal management of batteries for electric vehicles. Advances in battery technologies for electric vehicles, Elsevier, 2015,pp. 327–358.
[187] Z. Mao, et al., Recycling of electrolyte from spent lithium-ion batteries, Sustainability 3 (2024) 100015.
[188] Tu, J., et al., Comprehensive thermal-hydraulic performance and thermoelectric conversion efficiency of bionic battery waste heat recovery system. 2022. **48**: p. 104039.
[189] A.M. Domingues, R.G. de Souza, Review of life cycle assessment on lithium-ion batteries (LIBs) recycling, Sustainability 3 (2024) 100032.
[190] Tian, M.-W., et al., Economic cost and numerical evaluation of cooling of a cylindrical lithium-ion battery pack using air and phase change materials. 2022. **52**: p. 104925.
[191] H. Liu, et al., Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: a review, Energy Convers. Manag. 150 (2017) 304–330.
[192] A. Pesaran, A. Vlahinos, T. Stuart, Cooling and preheating of batteries in hybrid electric vehicles. 6th ASME-JSME Thermal Engineering Joint Conference, Citeseer, 2003.
[193] P.R. Tete, M.M. Gupta, S.S. Joshi, Developments in battery thermal management systems for electric vehicles: a technical review, J. Energy Storage 35 (2021) 102255.
[194] C. Yang, H.-J. Shi, Prospects of battery assembly for electric vehicles based on patent analysis, Int. J. Low. -Carbon Technol. 18 (2023) 1134–1139.
[195] H. Yurong, et al., Electric vehicle BMS subdivision technology patent distribution analysis, IOP Conf. Ser.: Mater. Sci. Eng. 631 (4) (2019) 042015.
[196] C. Spreafico, et al., Using patents to support prospective life cycle assessment: opportunities and limitations, Int. J. Life Cycle Assess. (2024).
[197] C. Spreafico, D. Landi, D. Russo, A new method of patent analysis to support prospective life cycle assessment of eco-design solutions, Sustain. Prod. Consum. 38 (2023) 241–251.
[198] Shahzad, R.F., et al. Designing composite materials by additive manufacturing for battery thermal management system (BTMS). in SAFECONOMY H2Economy: Hydrogen Economy Workshop. 2024.
[199] S. Wali, et al., Grid-connected lithium-ion battery energy storage system towards sustainable energy: a patent landscape analysis and technology updates, J. Energy Storage 77 (2024) 109986.