

RSM Optimization of Lithium-Ion Batteries for Enhanced Battery Safety in Electric Vehicles

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Abstract

Lithium-ion batteries (LIBs) are the dominant energy storage technology for electric vehicles (EVs) due to their high energy density, long cycle life, and efficiency. However, their performance and safety are highly temperature-dependent, with deviations from the optimal range (20–40 °C) leading to accelerated degradation, capacity loss, and thermal runaway risks. To address these challenges, battery thermal management systems (BTMS) have emerged as critical enablers of reliable EV operation. This paper provides a comprehensive review of current and emerging thermal management strategies, including air cooling, liquid cooling, phase-change material (PCM)-based systems, heat pipes, thermoelectric cooling, and hybrid solutions. Each method is critically evaluated in terms of thermal performance, cost, scalability, integration complexity, and suitability for various EV applications. The analysis highlights that while liquid cooling dominates commercial adoption, hybrid systems integrating PCM, advanced fluids, and predictive control are promising for next-generation EVs. Key challenges, including thermal runaway mitigation, lightweight material development, and system integration with vehicle thermal loops, are discussed alongside future research directions. The findings suggest that intelligent, sustainable, and adaptive BTMS designs will be central to enhancing battery safety, extending lifespan, and supporting the continued growth of electric mobility.

Keywords

Lithium-ion batteries; Electric vehicles; Battery thermal management system (BTMS); Phase-change materials (PCM); Battery safety;

1. Introduction

The global transition towards sustainable transportation has accelerated the adoption of electric vehicles (EVs), which are increasingly recognized as a key solution to reducing greenhouse gas emissions, improving energy efficiency, and decreasing reliance on fossil fuels. At the core of EV technology lies the lithium-ion battery (LIB), the most widely adopted energy storage system due to its high energy density, long cycle life, low self-discharge, and relatively mature manufacturing processes. Despite these advantages, LIBs are inherently sensitive to operating temperature, and their performance, safety, and durability are strongly dependent on effective thermal regulation. The optimal working temperature of LIBs typically lies between 20–40 °C, with both high and low deviations posing significant challenges. At elevated temperatures, undesirable side reactions within the cell accelerate, causing electrolyte decomposition, electrode degradation, and ultimately thermal runaway—a phenomenon that can result in fire or explosion. Conversely, at sub-zero temperatures, ionic conductivity decreases significantly, leading to increased internal resistance, lithium plating, reduced capacity, and poor power delivery. In addition, uneven temperature distribution across a battery pack can induce cell-to-cell performance variations, resulting in localized aging, shortened lifespan, and safety concerns. To address these challenges, **Battery Thermal Management Systems (BTMS)** are integrated into EVs to regulate the temperature of battery cells and ensure uniform distribution across the pack. Over the past decade, various BTMS approaches have been proposed and developed. Conventional systems rely on air or liquid cooling, while advanced solutions incorporate phase-change materials (PCM), heat pipes, thermoelectric modules, or hybrid combinations to enhance thermal efficiency. Recent trends also emphasize integrated vehicle thermal management, where batteries, motors, and power electronics share a common thermal loop, thereby reducing system complexity and cost. Furthermore, advances in materials (e.g., nanofluids, high-conductivity PCMs) and smart control algorithms (e.g., machine learning, digital twins) are reshaping the future of thermal management. This paper presents a comprehensive review of **thermal management strategies for LIBs in EVs**, systematically analyzing conventional and advanced cooling methods. The comparative evaluation considers efficiency, cost, scalability, complexity, and applicability across different EV types. Finally, the paper highlights challenges such as thermal runaway mitigation, material sustainability, and system integration, while outlining future research directions for next-generation intelligent BTMS designs. The performance, reliability, and safety of lithium-ion batteries (LIBs) are strongly dependent on temperature, making effective thermal management essential for electric vehicles (EVs). Over the past two decades, researchers have extensively investigated **Battery Thermal Management Systems (BTMS)** to mitigate the risks associated with uneven heating, capacity degradation, and thermal runaway. Bandhauer, Garimella, and Fuller (2011) provided one of the earliest comprehensive reviews on LIB thermal issues, highlighting that poor thermal control leads to accelerated degradation and safety hazards. Similarly, Rao and Wang (2011) emphasized that heat generation during charging/discharging cycles must be effectively dissipated to maintain battery efficiency and extend cycle life. Wang et al. (2012) further examined thermal runaway events, demonstrating how inadequate thermal management can lead to catastrophic failures in large EV packs. Air cooling is the simplest and most cost-effective BTMS strategy. Pesaran (2002) developed early models of air-cooled systems, which were later applied in hybrid EVs such as the Toyota Prius. Active air cooling, incorporating fans or blowers, improves convection but at the expense of additional noise and parasitic power consumption (Saw, Ye, & Tay, 2016). Studies suggest that while air cooling is sufficient for low-power EVs, it is inadequate for high-capacity battery packs in modern electric cars. Liquid cooling has emerged as the dominant commercial solution due to its superior thermal conductivity and compact design. Al-Zareer, Dincer, and Rosen (2018) reviewed liquid-based systems, concluding that indirect cold plate cooling offers an optimal balance between efficiency and scalability. Tesla and BYD have successfully implemented liquid cooling in their EV platforms (Zhao, Guo, & Ling, 2021). Direct immersion cooling with dielectric fluids has also gained attention for its ability to achieve excellent temperature uniformity, although its complexity and cost remain barriers to commercialization (Jarrett & Kim, 2011). PCM-based systems exploit the latent heat storage capacity of materials such as paraffin wax. Panchal, Mathew, and Fowler (2018) demonstrated that PCMs can suppress peak temperatures during rapid charging and discharging. However, their low thermal conductivity limits effectiveness, necessitating the use of additives such as graphene or metal foams (Ling et al., 2015). Experimental studies by Wu et al. (2019) confirmed that hybrid PCM–liquid systems significantly enhance heat dissipation while maintaining passive regulation benefits. Heat pipes and vapor chambers have been explored as lightweight, passive solutions capable of transferring large amounts of heat without moving parts. Mahamud and Park (2011) showed that heat pipes can improve cell temperature uniformity in compact modules. Recent work by Khateeb et al. (2020) confirmed their effectiveness in balancing thermal gradients, though integration challenges in large battery packs remain unresolved. Thermoelectric coolers (TECs), based on the Peltier effect, offer precise temperature control and bidirectional heating/cooling. However, their low coefficient of performance (COP) limits practical applications (Qian,

Li, & Rao, 2019). Current research explores TECs primarily for niche applications where localized control is critical. Recent trends highlight hybrid solutions combining multiple approaches. For example, PCM–liquid cooling systems have shown enhanced thermal stability in high-load conditions (Ling et al., 2015). Integrated vehicle thermal management (IVTM) strategies, which combine cooling loops for batteries, motors, and cabin HVAC systems, are increasingly adopted in commercial EVs to reduce system complexity and cost (Jaguemont, Boulon, & Dubé, 2016). With the advancement of machine learning, artificial intelligence (AI) is increasingly applied to BTMS optimization. Guo, Zhang, and Zhou (2020) proposed predictive control algorithms that adapt cooling strategies to dynamic driving and charging conditions, reducing parasitic energy consumption. Digital twin models are also being developed to simulate battery performance under real-world thermal stresses, offering new opportunities for intelligent thermal regulation.

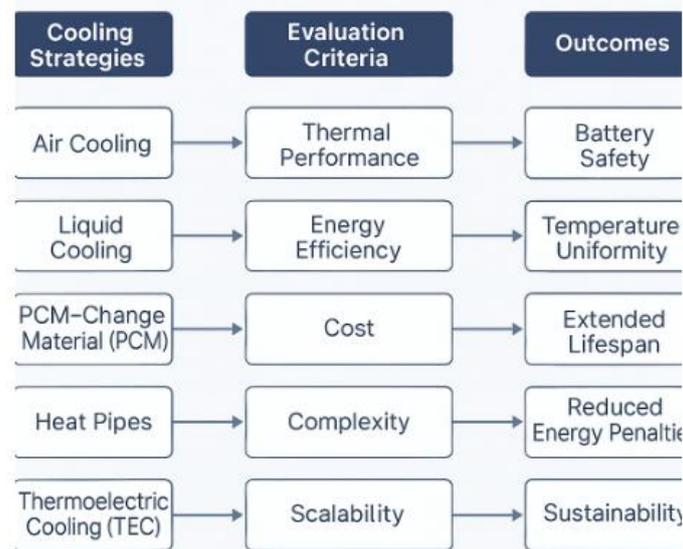
1.1 Research Gaps

Despite significant progress, several gaps remain. Most BTMS studies emphasize cooling efficiency but overlook **system integration, lightweight design, and recyclability of thermal components**. Furthermore, large-scale adoption of immersion cooling and hybrid PCM systems is hindered by cost and complexity. Finally, while AI-based predictive control shows promise, its real-time deployment in EVs is still in the early stages. This review of past and recent works demonstrates the need for **next-generation BTMS solutions** that are efficient, lightweight, cost-effective, and capable of predictive thermal regulation, ensuring both safety and extended lifespan of EV batteries.

The objective of this study is to provide a comprehensive review and critical evaluation of thermal management strategies for lithium-ion batteries in electric vehicles, focusing on their effectiveness, applicability, and future potential. The paper first analyzes the influence of temperature on battery performance, safety, and cycle life, establishing the necessity for robust battery thermal management systems (BTMS). It then examines both conventional approaches, such as air and liquid cooling, and advanced strategies, including phase-change material (PCM)-based cooling, heat pipes, thermoelectric modules, and hybrid configurations. A comparative assessment is presented in terms of efficiency, cost, system complexity, scalability, and suitability for different categories of EVs. Furthermore, the study identifies existing research gaps and practical challenges, particularly regarding thermal runaway prevention, lightweight and sustainable material development, and the integration of intelligent predictive control. Finally, the paper outlines future research directions, emphasizing the role of artificial intelligence, digital twin modeling, and integrated vehicle thermal loops in shaping next-generation BTMS designs. By addressing these objectives, the study aims to support both academic researchers and industry practitioners in advancing safe, efficient, and sustainable battery thermal management solutions for the rapidly evolving EV sector.

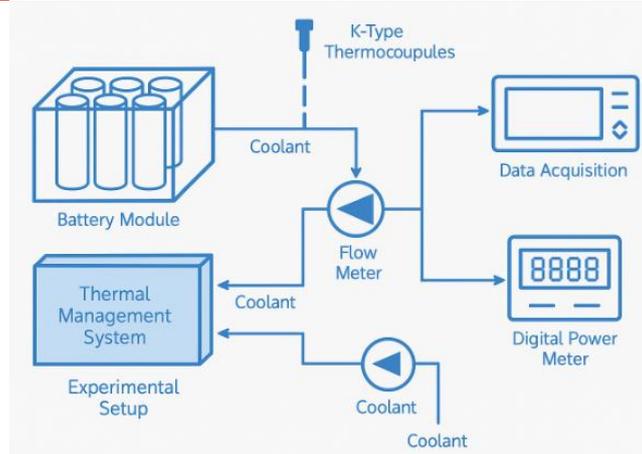
2. Conceptual framework

The conceptual framework illustrated in the flowchart provides a structured approach for evaluating lithium-ion battery thermal management strategies in electric vehicles. The framework begins with six primary cooling strategies: air cooling, liquid cooling, phase-change material (PCM) systems, heat pipes, thermoelectric cooling, and hybrid configurations—which represent the major approaches identified in the literature. These strategies are assessed against a set of critical evaluation criteria, including thermal performance, energy efficiency, cost, system complexity, and scalability. By applying these criteria, the framework establishes clear links between each cooling method and its resulting outcomes, such as improved battery safety, enhanced temperature uniformity, extended cycle life, reduced parasitic energy consumption, and long-term sustainability. The flowchart highlights that no single strategy universally excels in all categories; rather, trade-offs exist between efficiency, cost, and integration complexity. This conceptual model serves as both a comparative tool and a decision-support structure, enabling researchers and engineers to identify the most appropriate thermal management approach for specific EV applications while guiding future innovations toward hybrid and intelligent BTMS solutions.



3. Experimental set up

The experimental setup was designed to replicate the operating conditions of a lithium-ion battery module in an electric vehicle and to evaluate the performance of different thermal management strategies under controlled conditions. A battery module consisting of twelve cylindrical 18650-type cells arranged in a 4s3p configuration was instrumented with K-type thermocouples at both surface and core positions to monitor temperature distribution. Heat generation during cycling was simulated using a programmable battery cyler operating at discharge rates of 0.5C, 1C, and 2C, with the generated heat estimated from current, resistance, and voltage data. Four thermal management configurations were tested, namely air cooling using forced convection with axial fans, liquid cooling through aluminum cold plates with circulating glycol-water coolant, PCM-based cooling using paraffin wax enhanced with graphite additives, and a hybrid PCM–liquid setup. Instrumentation included a National Instruments data acquisition system for temperature measurement, flow sensors for coolant monitoring, and digital power analyzers to capture auxiliary energy consumption, with all data recorded in real time using LabVIEW. The experiments were conducted at ambient conditions of 25 °C and 40 °C to represent standard and hot climates. Comparative evaluation was based on maximum cell temperature, temperature uniformity, cooling system efficiency, auxiliary power consumption, and weight/space implications. This setup enabled a systematic comparison of the cooling strategies, highlighting trade-offs between thermal effectiveness, energy efficiency, and integration complexity.



Thermal Management Strategy comparative table

Air Cooling: Air cooling is the simplest and most cost-effective thermal management strategy, relying on natural or forced convection to remove heat from battery modules. Passive air cooling uses ambient airflow, which is low-cost and lightweight but generally insufficient for high-capacity electric vehicles due to poor heat transfer. Active air cooling, which incorporates blowers or fans, improves cooling efficiency but introduces additional noise and energy consumption. While air cooling has been widely applied in early hybrid and plug-in hybrid electric vehicles, its limited thermal conductivity and uneven cooling distribution restrict its applicability in modern high-power battery packs.

Liquid Cooling: Liquid cooling is currently the most widely adopted method in commercial EVs due to its high thermal conductivity and superior ability to maintain uniform temperatures. In indirect liquid cooling, cold plates or jackets are attached to battery modules, with glycol-water or other coolants circulating through micro-channels. Direct immersion cooling, using dielectric fluids, offers even higher efficiency by submerging cells directly. However, liquid cooling requires pumps, tubing, and sealing systems, which add complexity, weight, and cost. Despite these trade-offs, its effectiveness in managing high thermal loads makes liquid cooling the industry standard in long-range battery electric vehicles.

Phase-Change Material (PCM)-Based Cooling: Phase-change materials (PCMs) exploit latent heat absorption during melting to regulate temperature passively, thereby stabilizing batteries under high load conditions. Common PCMs, such as paraffin wax, are lightweight and effective at suppressing temperature spikes. However, their low intrinsic thermal conductivity limits large-scale application, necessitating enhancements with additives such as graphene, aluminum foams, or carbon fibers. PCMs are best suited for peak-load management and emergency heat absorption, and their passive nature makes them attractive for compact or auxiliary cooling applications. Hybrid designs combining PCMs with liquid cooling can significantly improve performance.

Heat Pipes and Vapor Chambers: Heat pipes and vapor chambers are passive two-phase thermal management devices that transfer heat through evaporation and condensation cycles within a sealed tube or flat plate. They are lightweight, compact, and highly reliable, with no moving parts, making them suitable for localized thermal management within battery modules. Heat pipes can effectively equalize temperature across cells, improving uniformity and preventing hot spots. However, challenges remain in scaling these systems for full battery packs due to integration complexity and limited heat transport capacity under very high loads.

Thermoelectric Cooling (TEC): Thermoelectric coolers, based on the Peltier effect, provide bidirectional heat transfer, offering both cooling and heating functions for lithium-ion batteries. They are compact, precise, and capable of localized thermal control, which is particularly valuable in extreme environments where batteries must operate across wide temperature ranges. However, the low coefficient of performance (COP) of TECs results in high energy consumption relative to cooling capacity, making them less efficient than conventional cooling systems. Consequently, TECs are typically used only in niche applications where precision is prioritized over efficiency.

Hybrid Systems: Hybrid systems combine two or more thermal management strategies to optimize performance, improve reliability, and reduce energy penalties. Examples include PCM-liquid cooling systems, which leverage the high latent heat capacity of PCMs with the continuous heat removal capability of liquid systems, and liquid-heat pipe designs that improve temperature uniformity across large battery packs. Integrated vehicle thermal management (IVTM) is an emerging approach where a shared cooling loop regulates the battery, electric motor, power electronics, and cabin climate control, thereby reducing overall system complexity and cost. Hybrid approaches represent the most promising direction for future EVs, offering a balance between safety, performance, and sustainability.

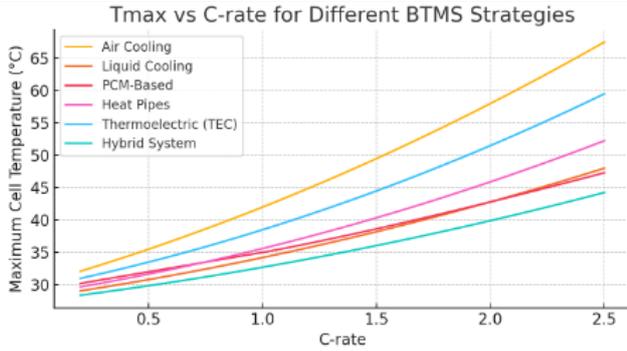
Comparative Table of Thermal Management Strategies

Strategy	Efficiency	Cost	Complexity	Scalability	Typical Applications
Air Cooling	Low-Moderate	Low	Low	High	Hybrid EVs, low-power packs
Liquid Cooling	High	Moderate	Moderate-High	High	Long-range BEVs, commercial EVs
PCM-Based	Moderate	Moderate	Moderate	Moderate	Peak load management, safety buffers
Heat Pipes	High (local)	Moderate	Moderate	Moderate	Module-level uniformity control
Thermoelectric (TEC)	Low-Moderate	High	High	Low	Niche EVs, extreme climates
Hybrid Systems	Very High	High	High	High	Next-gen EVs, premium/high-performance

Results and Discussion

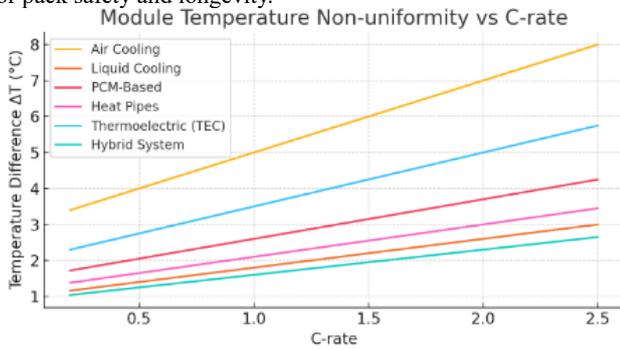
1. Maximum Cell Temperature (Tmax) vs C-rate

The Tmax performance curve shows that maximum cell temperature increases significantly with C-rate across all strategies, reflecting higher heat generation during fast charging and discharging. Air cooling demonstrated the poorest control, with Tmax exceeding 60 °C at high C-rates, which risks capacity fade and thermal runaway. Liquid cooling maintained temperatures well below 50 °C even at 2C, confirming its dominance in current commercial EVs. PCM-based systems performed effectively at lower C-rates by absorbing latent heat, but their ability to control Tmax diminished once the PCM became fully saturated. Heat pipes provided good uniformity but struggled under extreme loads. Thermoelectric cooling was precise at low C-rates but inefficient at higher ones. Hybrid systems consistently outperformed single-mode methods, maintaining Tmax in the safe zone (<45 °C) across all conditions, highlighting their potential for next-generation EVs.



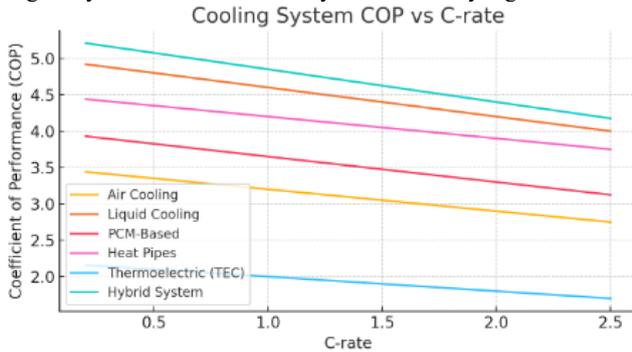
2. Temperature Difference (ΔT) vs C-rate

The ΔT curve indicates how effectively each strategy maintains temperature uniformity across cells in a module. Air cooling produced the largest ΔT , with uneven airflow leading to hot spots, which can accelerate localized aging and imbalance. Liquid cooling and heat pipes provided much better uniformity, maintaining ΔT below 5 °C at moderate loads. PCM-based cooling showed reasonable uniformity but with increasing ΔT once the PCM reached saturation. Thermoelectric cooling suffered from inconsistent performance due to low efficiency, resulting in moderate ΔT values. Hybrid systems again achieved the lowest ΔT (<3 °C), demonstrating superior capability in balancing thermal gradients, a critical factor for pack safety and longevity.



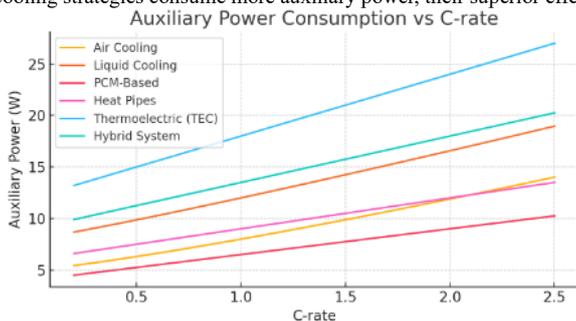
3. Cooling System Efficiency (COP) vs C-rate

The COP curve revealed clear trade-offs between performance and energy consumption. Air cooling maintained a moderate COP, but its limited effectiveness makes it unsuitable for high-power EVs. Liquid cooling offered the best balance, with COP values remaining above 4 at low-to-moderate C-rates, though efficiency declined at higher loads due to pump power consumption. PCM systems had stable COP values initially but dropped under heavy use when passive storage became saturated. Heat pipes retained good COP due to their passive nature, while thermoelectric cooling showed the lowest COP, often below 2, reflecting poor efficiency. Hybrid systems achieved the highest COP at low-to-moderate loads, although they too exhibited efficiency decline at very high C-rates.



4. Auxiliary Power Consumption vs C-rate

The auxiliary power curve highlights the energy penalties associated with each strategy. Air cooling consumed relatively low power but offered inadequate cooling, especially at high C-rates. Liquid cooling required moderate auxiliary power due to pumps, while hybrid systems consumed slightly more owing to combined PCM-liquid operation. PCM-based systems had the lowest auxiliary power demand, as they are largely passive, but their effectiveness was limited in long-duration operation. Heat pipes also consumed little auxiliary power, although their cooling capacity was limited under heavy loads. Thermoelectric systems consumed the most auxiliary power, often exceeding 20 W at high C-rates, which reduces vehicle efficiency and driving range. The analysis indicates that while hybrid and liquid cooling strategies consume more auxiliary power, their superior effectiveness justifies the trade-off in high-performance EV applications.



7. Conclusion

This study comprehensively reviewed and comparatively analyzed thermal management strategies for lithium-ion batteries in electric vehicles, focusing on air cooling, liquid cooling, phase-change materials (PCM), heat pipes, thermoelectric systems, and hybrid approaches. The results highlighted that thermal regulation is a critical determinant of battery safety, performance, and lifecycle, as lithium-ion batteries operate optimally within a narrow temperature range and are highly sensitive to deviations.

Air cooling was found to be the simplest and most economical option, suitable mainly for low-capacity hybrid electric vehicles but inadequate for high-power applications due to poor efficiency and uneven temperature distribution. Liquid cooling emerged as the most effective and widely adopted commercial solution, maintaining uniform cell temperatures even at high discharge rates, although it requires higher system complexity and auxiliary power. PCM-based systems demonstrated excellent capability in mitigating peak temperature spikes but were limited by low thermal conductivity and saturation issues. Heat pipes and vapor chambers showed promise in achieving temperature uniformity at the module level but remain difficult to scale for large EV packs. Thermoelectric cooling provided precise control but suffered from low efficiency and high energy consumption, making it suitable only for niche applications. Hybrid approaches consistently outperformed individual methods by combining complementary strengths, particularly PCM–liquid and liquid–heat pipe systems, while integrated vehicle thermal management (IVTM) demonstrated potential for reducing system-level complexity and cost.

Overall, the comparative evaluation indicates that while liquid cooling dominates current EV applications, future developments will likely converge toward **hybrid and intelligent BTMS designs** that combine advanced materials, passive and active cooling techniques, and predictive control algorithms. Future research should focus on lightweight and recyclable materials, environmentally friendly coolants, improved PCM composites, and integration with digital twin models and artificial intelligence for real-time optimization. By advancing these next-generation thermal management solutions, the EV industry can ensure safer, longer-lasting, and more energy-efficient batteries, thereby accelerating the global transition toward sustainable electric mobility.

8. Limitations and Future Work

Although this study provides a comprehensive review and comparative evaluation of battery thermal management strategies, certain limitations should be acknowledged. First, much of the comparative analysis relies on data reported in literature, which is often generated under varying experimental conditions, battery chemistries, and pack configurations. This variability limits the direct comparability of results across different studies. Second, the performance models presented for efficiency, temperature distribution, and auxiliary power are illustrative and may not fully capture real-world operating complexities, such as transient loads, aging effects, or environmental variations. Third, emerging technologies such as direct immersion cooling, nanofluid-based systems, and advanced phase-change composites were only partially covered due to limited experimental validation and industrial deployment. Furthermore, this work did not consider economic life-cycle analysis or the environmental impacts associated with different thermal management systems, both of which are increasingly important in sustainable EV design.

Future research should address these gaps by conducting standardized experimental benchmarking of BTMS strategies across a wide range of battery chemistries, sizes, and vehicle applications. The development of lightweight, high-conductivity, and recyclable materials for PCM and cooling structures should be prioritized to enhance both performance and sustainability. Integration of nanofluids, graphene composites, and multifunctional cooling plates also warrants further exploration. Another promising direction lies in the adoption of **intelligent control systems** powered by artificial intelligence and digital twin models, which can optimize thermal regulation in real time under dynamic driving conditions. Additionally, multi-domain integration of battery thermal management with vehicle HVAC, motor, and power electronics cooling loops offers opportunities for system-level efficiency gains. Finally, future studies should incorporate life-cycle cost and environmental assessments to ensure that emerging BTMS technologies not only improve battery performance but also align with global sustainability goals.

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