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Critical Review on Multifunctional Polymer Composites for Weight Reduction and AI Based Battery Thermal Management in Electric Vehicles

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Abstract

The rapid growth of electric vehicles (EVs) has intensified the need for advanced materials and intelligent control systems capable of improving energy efficiency, driving range, thermal safety, and overall vehicle sustainability. This paper presents a critical review of multifunctional polymer composites and artificial intelligence-based battery thermal management systems (AI-BTMS) for next-generation EV applications. Polymer composites reinforced with carbon fibers, graphene, boron nitride, nanoclays, and carbon nanotubes offer significant advantages over conventional metallic materials due to their low density, high specific strength, corrosion resistance, design flexibility, and potential for multifunctional integration. Their use in chassis structures, battery enclosures, and protective casings contributes to substantial vehicle lightweighting while also enabling additional functions such as thermal conduction, electromagnetic interference shielding, and structural sensing. In parallel, AI-based thermal management strategies employing artificial neural networks, fuzzy logic, reinforcement learning, support vector regression, and hybrid deep learning models have emerged as powerful tools for real-time temperature prediction, anomaly detection, adaptive cooling control, and energy optimization in lithium-ion battery systems. This review critically compares material classes, processing approaches, thermal conductivity enhancement routes, hybrid cooling mechanisms, and data-driven control strategies relevant to EV design. The analysis shows that the integration of multifunctional composites with intelligent thermal control can reduce structural mass, improve battery safety, lower parasitic energy losses, and extend operational range. The paper further discusses sustainability considerations, manufacturing scalability, cost–performance trade-offs, and industrial adoption challenges. It concludes that the convergence of material innovation and AI-enabled control provides a promising pathway toward lightweight, thermally stable, energy-efficient, and environmentally responsible electric mobility systems.

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Keywords: Polymer composites, electric vehicles, weight reduction, battery thermal management, artificial intelligence, nanomaterials, sustainability

INTRODUCTION

The electrification of transportation has become one of the most significant technological transitions of the twenty-first century due to the urgent need to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and promote sustainable mobility. At the center of this transition are electric vehicles (EVs), which rely on high-efficiency propulsion systems powered by rechargeable battery technologies. However, challenges related to structural weight, battery performance, thermal safety, and energy efficiency continue to limit the achievement of long driving range and high operational reliability. In this context, multifunctional polymer composites have emerged as promising materials for reducing structural mass while improving mechanical strength, corrosion resistance, and functional integration [1]. In parallel, artificial intelligence (AI) is increasingly being incorporated into battery thermal management systems (BTMS) to monitor, predict, and regulate heat generation and dissipation in EV battery packs, thereby improving safety, durability, and energy utilization [4, 7, 26]. The convergence of these two domains—advanced composite materials and AI-driven thermal intelligence—represents a transformative direction for the development of next-generation electric mobility systems.

The EV manufacturers of this type pay significant attention to the design consideration of lightweighting because it directly affects the battery demand, the driving range, and the energy efficiency. Although they provide structural rigidity, the traditional metallic materials like steel and aluminum add a lot of mass to a vehicle and hence uses a lot of energy per kilometer [5]. Conversely, carbon fiber, glass fiber, or nanomaterials (graphene and carbon nanotubes) reinforced polymer composites offer a very promising combination of low-weight properties, high specific strength, and excellent fatigue resistance [6]. It has been shown that the use of polymer composites as substitutes to conventional metals in structural and semi-structural EV parts can reduce weight by 30 to 50 percent, leading to a 10 to 15 percent range improvement with no change in battery properties [7]. Table 1 shows the mechanical and physical characteristics of typical structural materials used in the design of EV.

As it has been mentioned, using carbon fiber and graphene-reinforced polymer can significantly decrease the weight of the vehicle without mechanical failure. They also have good corrosion resistance profiles and this adds to the sustainability of EVs in the long term. Moreover, multifunctional composites do not only play structural, but can also be used to incorporate functional capabilities, such as electrical conductivity, thermal control, and damage detection, which render them perfect towards state-of-the-art EV architectures [9].

Lightweighting however, improves energy efficiency, but as the density of the energy available in batteries increases, the thermal management of the batteries becomes increasingly complicated. The greatest temperature changes occur in lithium-ion batteries, which are the most common energy storage in EV models. High heat dissipation during charging, discharging or under high load conditions may result in accelerated degradation, lower capacity, and could also result in safety risks such as thermal runaway [10]. Traditional BTMS methods (relying on either passive cooling, air cooling, or liquid cooling) are in many cases passive in nature and do not dynamically adjust to real time temperature changes and loads. This drawback has inspired the incorporation of AI-based thermal management, which uses data analytics and predictive modeling to promote the cooling efficiency, reduce power waste, and provide safety in its operations [11].

AI-based BTMS is based on machine learning (ML) and deep learning (DL) algorithms to work with real-time data of various sensors in battery modules. Such algorithms are able to calculate the rate of heat generation, optimize the flow of cooling fluid and regulate the fan speed or the operation of a coolant pump to ensure an optimum thermal environment. As an example, reinforcement learning models can be trained to automatically discover the correlation between driving behavior, ambient conditions and battery heating cycle to permit adaptive thermal control [12]. Table 2 summarizes various AI methods used in BTMS and the results of their performance.

Table 1. Comparative properties of conventional and composite materials used in EV structures [8].

Material Type	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Corrosion Resistance	Weight Reduction (%)
Mild Steel	7.8	370	210	Low	–
Aluminum Alloy	2.7	320	70	Moderate	40
Carbon Fiber Composite	1.6	800	150	Excellent	60
Glass Fiber Composite	2.0	500	80	High	45
Graphene Reinforced Polymer	1.4	1200	200	Excellent	65

Table 2. AI techniques for battery thermal management in electric vehicles [13].

AI technique	Input parameters	Key function	Performance advantage	Example application
Artificial Neural Network (ANN)	Temperature, Voltage, Current	Predict thermal gradient	High accuracy in temperature prediction	Thermal fault detection
Fuzzy Logic Control (FLC)	Ambient temp., charge rate	Dynamic cooling control	Smooth adaptation to uncertain environments	Real-time fan speed control
Reinforcement Learning (RL)	Battery state, driving profile	Optimize control actions	Self-learning for minimum energy loss	Adaptive coolant flow
Support Vector Regression (SVR)	Load current, SOC	Predict future temperature	Effective for non-linear systems	Smart cooling scheduling
Genetic Algorithm (GA)	Design parameters	Optimize BTMS configuration	Faster convergence	Hybrid thermal control system

These smart systems can be used to adjust the control strategies on a real-time basis and make sure that the battery runs within a safe temperature range (20–45 o C) under different conditions. Lightweight polymer composites together with AI-based BTMS is a two-fold advantage: it both saves energy at the material level and provides optimization of efficiency at the system level. The outcome of such integration is reduced parasitic power consumption by cooling systems and an improvement in vehicle performance indicators, such as range and battery life [14].

Thermal and electrical conductivity tuning of multifunctional polymer composites is another important dimension of multifunctional polymer composites. Nanofiller additions to the polymer matrix (e.g., graphene, carbon nanotubes, or boron nitride) improve the heat dissipation and electromagnetic interference (EMI) shielding, essential to safety in EV batteries and power electronics. These composites may serve as thermal conductive encasements or casings of batteries and, thus, contribute to passive heat conduction in addition to eliminating the reliance on active cooling systems [15]. In this way, the concept of multifunctionality is expanded beyond mechanical strength to thermal protection and electrical protection.

Polymer composites are also sustainable and have environmental advantages. A large number of composites are currently created using bio-based polymers or recyclable polymers, which conforms to the principles of global circular economies. The lower mass of the vehicles also reduces energy use during the lifetime of the vehicle, which reduces indirectly the emission of greenhouse gases. Such systems when synergistically coupled with AI optimization have synergistic sustainability impacts - where material innovation enhances smart operation to generate greener mobility.

Besides, polymer composites can be engineered with a high level of manufacturing flexibility, which can be used to incorporate sensors, actuators, and conductive traces into the structure that can be smart composites that can measure strain, temperature, or impact in real time. These integrated sensors can also be used as additional sources of information into the AI-based systems to predictive maintenance, fault detection, and automatic optimization of performance - a new dawn of smart materials to smart mobility.

Although such advancements have been made, there are still a number of gaps in research. The problems have been the enhancement of the interfacial bonding of polymer matrices and nanofillers, uniform dispersion of conductive additives, and cost-effective mass production methods. With regard to the AI, it is also critical to guarantee the robustness, interpretation, and the calculation efficiency of predictive algorithms in real-world scenarios. The design of materials with AI systems, which involves data-driven insights that inform composite fabrication and vice versa, is one of the future stages of EV innovation.

To sum up, multifunctional polymer composites and AI-based thermal management of batteries are the key to the future of EV design. All these technologies are aimed at addressing the main challenges of performance and sustainability in electric mobility by reducing weight, improving energy efficiency and smart thermal regulation. Future interdisciplinary studies combining materials science, data analytics, and thermal engineering will play a central role in the achievement of lightweight, safe, and intelligent electric vehicles that can contribute to the idea of the low-carbon future.

REVIEW METHODOLOGY

This paper adopts a structured narrative review approach to critically examine the role of multifunctional polymer composites and artificial intelligence-based battery thermal management systems in electric vehicles. Although the present work is not intended as a full systematic review or meta-analysis, a transparent literature selection strategy was followed in order to improve methodological rigor, reproducibility, and thematic consistency. The review was designed to capture studies related to lightweight structural materials for EVs, thermally conductive polymer composites, phase change and hybrid cooling materials, machine learning and deep learning methods for battery thermal management, and integrated smart material–control architectures.

The literature survey was conducted using major scholarly databases including Scopus, Web of Science, ScienceDirect, IEEE Xplore, SpringerLink, and Google Scholar. Keywords and Boolean combinations used during the search included: *"electric vehicles"*, *"polymer composites for EVs"*, *"multifunctional composites"*, *"graphene reinforced polymer"*, *"boron nitride epoxy thermal conductivity"*, *"battery thermal management system"*, *"AI in battery thermal management"*, *"machine learning for EV thermal control"*, *"reinforcement learning BTMS"*, and *"smart materials for EV batteries"*. Priority was given to peer-reviewed journal articles, high-quality conference papers, and recent review papers published mainly in the last decade, with additional foundational studies included where necessary to establish context.

The initial search yielded a broad pool of publications across materials science, thermal engineering, computational intelligence, and electric mobility. These records were then screened on the basis of relevance to the core themes of the paper. Studies were included if they addressed at least one of the following: (i) lightweight and high-performance polymer composite materials for EV structures or battery enclosures, (ii) thermally conductive or multifunctional composites with additional properties such as EMI shielding, flame resistance, or sensing capability, (iii) AI, machine learning, or optimization algorithms applied to battery thermal prediction, control, or fault diagnosis, and (iv) hybrid frameworks combining material design and intelligent thermal control. Studies with weak technical relevance, insufficient experimental or analytical detail, duplicate reporting, or applications unrelated to EV systems were excluded.

After screening and thematic filtering, 29 key references were retained for detailed analysis in this review. These studies were categorized into major analytical themes: structural lightweighting, thermal conductivity enhancement, multifunctionality and sustainability of polymer composites, AI techniques for BTMS, predictive and adaptive control strategies, and industrial scalability challenges. Comparative synthesis was then performed using tabular analysis and cross-sectional discussion of materials, methods, performance indicators, and practical limitations. This approach enabled the paper to move beyond a purely descriptive summary and instead provide an analytical interpretation of how materials innovation and intelligent thermal control are converging in next-generation EV design.

While the adopted review methodology improves transparency, the authors acknowledge that the present study remains a structured critical review rather than a formal systematic review with bibliometric mapping or statistical meta-analysis. Future review work may further strengthen the field by applying PRISMA-based screening frameworks, citation network analysis, and quantitative evidence synthesis. Nevertheless, the present methodology provides a sufficiently rigorous foundation for identifying major research trends, comparing technological pathways, and highlighting future opportunities in lightweight, thermally stable, and intelligent electric vehicle systems.

RELATED WORKS

The growing demand for lightweight, energy-efficient, thermally safe, and sustainable electric vehicles has accelerated research on two closely related technological areas: multifunctional polymer composites and intelligent battery thermal management systems. These developments are increasingly central to EV design, where structural efficiency, thermal control, safety, and smart operation must be addressed simultaneously. The available literature shows substantial progress in both domains: first, in the development of lightweight, thermally conductive, and multifunctional polymer composites for structural and protective EV applications; and second, in the use of artificial intelligence and machine learning techniques for predictive, adaptive, and energy-efficient thermal management of lithium-ion batteries.

The study of polymer composite in EVs has been developed very significantly in the past decade particularly regarding the use of nanostructural fillers like graphene, boron nitride (BN), and carbon nanotubes (CNTs). Azzopardi et al. [1] pointed out that highly developed polymer composites remarkably enhance the mechanical strength to weight ratio of EV battery packs resulting to more than a 40 percent decrease in vehicle mass and enhanced energy efficiency. On the same note, Gupta et al. [8] and Sahu and Rizwan [18] observed that multifunctional composites combine mechanical resilience with other capabilities, including electrical conductivity, EMI shielding, and flame retardancy-structural and protective capabilities in one material. Experiments by Ghosh et al. [5] and Singh et al. [22] affirmed that carbon or glass fiber reinforced hybrid polymer matrices would perform better in dynamic loads, and can be used as an alternative to aluminum alloys in chassis and enclosure.

In the perspective of sustainability, bio-based and recyclable composites have been of interest as a result of environmental regulations and efficiency of lifecycle. The systematic reviews above (Dobrotă et al. [3]) and (Singh et al. [22]) focus on the idea of renewable polymers such as polylactic acid (PLA) and natural fiber composite being able to retain high thermal stability and minimize carbon footprint by 30%. Sharma et al. [19] further extended this idea through connecting polymer design to energy storage to demonstrate how conductive polymer matrices may be utilized as mechanical parts and supercapacitor active electrodes. This is in line with the areas of the circular economy in the production of EVs.

Polymer composite based battery housings and module packaging have also become central to use of thermally conductive polymer composites. Li et al. [13] and Shekari et al. [21] also indicated that the addition of either graphite, BN, or CNT fillers to polymer matrix results in a significant improvement of anisotropic heat conduction such that localized heat generated within densely packed cells is dissipated effectively. What was shown by Shchegolkov et al. [20] is the presence of smart polymer composites which have the electrical heating capability and hence they will be capable of warming themselves in sub-zero temperatures. These materials are also especially helpful in ensuring the stability of work without the use of extra heating equipment. In connection, Zhou et al. [29] introduced ultra-high thermal conductively composites using uniaxially oriented BN sheets having conductivity of more than 50 W/m3K conductor that can be used in both wireless charging and thermal interface material (TIM) applications.

Kibria et al. [12] and Togun et al. [25] were concerned with composite phase change materials (PCMs) and hybrid nanofluids in passive battery cooling. Their publications confirmed that the PCM-impregnated composites with nanostructured additives (graphene, Al 2 O 3, SiC) provide a 40 45 percent higher uniformity of temperature in battery modules. These findings were corroborated by Tawiah et al. [24], who emphasized that carbon-based composites have two advantages in terms of thermal conduction and flame retardancy, which implies that the operation of battery under faulty conditions is safer. Similarly, He et al. [9] and Boretti [2] noted that the hybrid cooling schemes (air, liquid, and PCM) combined with composite materials will improve the dependability and the longevity of lithium-ion battery systems.

With the increasing complexity of EV systems, AI and machine learning (ML) have proved to be potent mechanisms of streamlining the operation of BTMS. The use of AI-based multiphysics models in predictive thermal management to allow the real-time observation of temperature anomalies and adaptive cooling was thoroughly reviewed by Ghalkhani and Habibi [4] and Goswami [7]. Khan et al. [11] designed a machine learning-based optimization of a U-shaped liquid-cooled BTMS that attained the 22-percent decrease in the largest temperature relative to the traditional designs. Su et al. [23] also provided multi-objective optimization models that combine ML and computational fluid dynamics (CFD) which exhibit better tradeoffs between cooling and energy cost.

Joint data-based models and physics-based simulations is one of the significant advances to autonomous and adaptive BTMS. Ghosh et al. [6] built an overall framework that used density functional theory (DFT), topology optimization, and machine learning (ML) to design an effective battery module. Their hybrid model system minimized the hotspots by 18 percent and enhanced the mechanical toughness. Other studies such as those by Ramasubramanian et al. [17] and Wang [26] indicated that reinforcement learning and deep neural networks can be used to create self-learning BTMS, which is able to reduce energy loss and also balance between battery temperature ranges. These systems vary the coolant flow rates, fan speed or PCM usage as a result of driving conditions and state-of-charge levels.

At the component level, Jadhav and Londhe [10] studied the coatings of heat sinks which improve the radiative cooling characteristics when combined with smart AI control leading to an increase in the rate of heating heat sinks by 15 to 20 percent. This was further elaborated by Martin et al. [14], who assessed AI-controlled power electronics cooling, in which case predictive control algorithms guarantee homogenous heat distributions in inverters and converters. Ortiz et al. [15] and Paneerselvam et al. [16] have reviewed hybrid cooling strategies using phase change cooling and liquid cooling system with fuzzy logic control and reported up to 12 percent of energy saving in auxiliary systems.

Intelligence systems of recent material orientation even blur the line between composite materials and AI integration. Wang et al. [27] created molecular-engineered aerogels that are stable at room temperature up to 1300C, self-powered sensors and electromagnetic interferences (EMI) shields predictive battery safety. Equally, Zhang et al. [28] proposed the idea of smart batteries featuring inbuilt AI surveillance and predictive failures. Combined, these works are an indication of the beginning of material-level intelligence, in which polymer composites themselves become thermal regulators as well as data collectors.

Altogether, the literature shows that there is a strong synergy between AI-based BTMS frameworks and multifunctional polymer composites. The composites guarantee the structural stability, mass minimization, and passive thermal regulation, whereas AI algorithms control moving heat flows and foresee the anomalies. Key developments in polymer composites to use in EVs are listed in Table 3 and the key AI-based BTMS approaches are listed in Table 4 and both disciplines develop together to achieve safe and energy-efficient electric mobility.

Table 3. Developments in multifunctional polymer composites for electric vehicles.

Focus Area	Composite Type	Functional Attributes	Reported Improvement	Reference
Structural Lightweighting	CFRP, GFRP, CNT-based	High stiffness, reduced density	40–60% weight reduction	[1, 5, 8, 22]
Thermal Conductivity	Graphene, BN, CNT-filled polymers	Enhanced heat dissipation	3–6× thermal conductivity increase	[9, 13, 21, 29]
Smart/Heating Composites	Conductive polymer foams, aerogels	Self-regulated heating, EMI shielding	Operation up to 1300°C	[20, 27]
Phase Change Materials	PCM + Nanofillers	Uniform heat spreading	45% lower hotspot gradient	[12, 24, 25]
Sustainability	PLA/Natural Fiber Composites	Renewable, recyclable	30% CO_2 reduction over lifecycle	[3, 19, 22]

The studies reviewed all show that lightweight polymer composites and AI-based intelligent BTMS has ceased to be an independent innovation but a mutually supporting part of an EV system design. Not only do the multifunctional composites substitute the conventional metals improving the structural/thermal aspects, but also serve as enablers of inbuilt sensations and heat. In its turn, AI algorithms use these material advantages to do real-time control, predict anomalies, and optimization of the system. Collectively they combine synergistic paradigm of intelligent, sustainable and high-performance EV architecture, to guarantee higher driving range, less energy loss, and higher safety- is a step towards the next generation of intelligent electric mobility.

CRITICAL ANALYSIS OF METHDOLOGIES AND RESULTS

The reviewed literature on multifunctional polymer composites and AI-based battery thermal management systems in electric vehicles reveals a strong convergence among materials engineering, thermal science, computational intelligence, and energy optimization. Collectively, these studies demonstrate that structural lightweighting, thermal conductivity enhancement, battery safety, and intelligent real-time control are no longer independent research themes, but interlinked elements of next-generation EV architecture.

To provide a clearer analytical interpretation, this section critically evaluates the literature across four dimensions: (i) material innovation and structural advancement, (ii) thermal management efficiency, (iii) AI and data-driven control integration, and (iv) sustainability, multifunctionality, and industrial relevance.

Material Innovation and Structural Advancement

Recent studies highlight the importance of the fact that shift in metallic materials to polymer composite materials dramatically increases the weight reduction, thermal regulation, and mechanical stability. Such materials, including carbon fiber-reinforced polymers (CFRPs) and graphene composites were highlighted by Azzopardi et al. [1] and Gupta et al. [8] to be used in structural applications, reaching a 40-60% reduction in vehicle mass and significant improvements in stiffness. Li et al. [13] and Zhou et al. [29] also showed that boron nitride (BN)- and graphene-filled polymers can achieve anisotropic thermal conductivity values above 5 W/m·K, compared with approximately 0.3 W/m·K for unfilled polymers. To compare the practical relevance of different composite systems for EV applications, Table 5 summarizes their density, thermal conductivity, weight-reduction potential, and key functional benefits.

From this analysis, graphene- and BN-based polymer composites emerge as the most effective in achieving combined structural and thermal benefits. However, the processing uniformity and filler dispersion challenges remain bottlenecks for scalable industrial applications.

Table 4. AI-based thermal management strategies in electric vehicles.

AI technique	Key function	Application area	Performance outcome	Reference
ANN / Deep Learning	Predict temperature & faults	Li-ion battery modules	>95% accuracy in anomaly detection	[4, 7, 28]
Reinforcement Learning	Adaptive coolant control	Dynamic BTMS	18% efficiency gain	[17, 26]
Support Vector Regression	Temperature forecasting	PCM–liquid hybrid BTMS	Reduced peak temp. by 10°C	[11, 15]
Fuzzy Logic Control	Real-time cooling optimization	Liquid/air hybrid systems	12% power saving	[14, 15, 16]
Multiphysics + ML	Coupled thermal-mechanical modeling	Battery module design	20°C reduction in hotspots	[6, 23]
Predictive Coating Optimization	Heat sink management	Power electronics cooling	15% improved heat dissipation	[10, 14]

Thermal Management and Heat Regulation Efficiency

Thermal stability and heat regulation of the lithium-ion batteries are the keys to their long-term stability and safety. He et al. [9], Kibria et al. [12], and Togun et al. [25] emphasized hybrid cooling made with the use of phase change materials (PCMs) and nanofluids, which increased the temperature evenness up to 45 percent and minimized the appearance of hotspots. In the meantime, Shchegolkov et al. [20] and Wang et al. [27] have suggested smart polymer-based aerogels to self-heat and EMI shielding, extending the thermal property over the temperature limits.

The data show that hybrid PCM–liquid systems provide the most balanced combination of cooling performance and energy efficiency. The integration of AI control algorithms further enhances dynamic response by anticipating load variations and adjusting coolant flow or fan speed accordingly.

Integration of AI and Data-Driven Thermal Control

The integration of AI in BTMS introduces real-time prediction and intelligent adaptation. Ghalkhani and Habibi [4] and Khan et al. [11] used machine learning (ML) models to predict temperature gradients and optimize cooling channel geometry, achieving 22% reduction in thermal peaks. Reinforcement learning approaches by Wang [26] and Ramasubramanian et al. [17] autonomously optimized thermal strategies, reducing energy consumption in auxiliary systems by 10–15%.

The table indicates that deep learning and hybrid ML models outperform traditional rule-based systems by providing predictive adaptability. The coupling of physics-based simulations with AI ensures system resilience and reduced computational delay, marking the onset of autonomous EV thermal ecosystems.

Table 5. Comparative evaluation of polymer composites for EV applications.

Composite type	Primary reinforcement	Density (g/cm^3)	Thermal Conductivity (W/m·K)	Weight reduction (%)	Key findings
CFRP	Carbon Fiber	1.6	2.5–5.0	60	Excellent mechanical strength and lightness
GFRP	Glass Fiber	2.0	1.0–1.5	45	Cost-effective, moderate conductivity
Graphene–Polymer	Graphene Nanosheets	1.4	6.0–8.5	65	Exceptional conductivity and EMI shielding
BN–Epoxy	Boron Nitride Sheets	1.5	7.2	55	High heat dissipation and insulation stability
CNT–Polymer	Carbon Nanotubes	1.3	4.8	58	Improved structural integrity, lightweight
PLA–Natural Fiber	Flax/Jute	1.1	0.5	40	Sustainable but limited heat resistance

Table 6. Comparative performance of thermal management systems.

Cooling Mechanism	Material/Method	Peak Temperature (°C)	Temperature Uniformity (%)	Response Efficiency	Remarks
Air Cooling	Ducted flow, fans	48–55	70	Moderate	Low-cost, high noise, uneven cooling
Liquid Cooling	Water/glycol channels	35–40	85	High	Effective for large modules
PCM Cooling	Paraffin + Graphene	37–42	90	Slow	Maintains steady temperature during cycles
Nanofluid Cooling	Al_2O_3–Water base	34–39	92	Very High	Enhanced heat exchange rate
Hybrid (PCM + Liquid)	PCM + Coolant	33–38	95	High	Optimal for long-range EVs
Smart Composite Aerogel	Polymer/Carbon blend	30–36	96	Very High	Combines insulation and EMI shielding

Table 7. Comparative analysis of AI algorithms in BTMS.

AI Technique	Input Parameters	Target Function	Prediction Accuracy (%)	Energy Savings (%)	Application Scope
ANN / CNN	Temp., SOC, current	Predict hotspot formation	95	12	Battery packs and modules
Fuzzy Logic	Ambient temp., load	Adaptive fan control	89	10	Air/liquid hybrid BTMS
Reinforcement Learning	Drive profile, SOC	Dynamic control optimization	93	15	Intelligent BTMS control
Genetic Algorithm	Geometry, flow rate	Multi-objective optimization	87	11	Cooling channel design
Multiphysics + ML	CFD + data fusion	Thermal–mechanical coupling	96	13	Real-time thermal prediction
Hybrid DL Models	Historical and live data	Predictive fault detection	98	14	Battery safety and diagnostics

Table 8. Sustainability and multifunctionality assessment of composite materials.

Material Type	Sustainability Index	Functional Integration	EMI Shielding (dB)	Flame Resistance	Key Application
PLA–Flax Composite	High	Structural + Insulation	30	Moderate	EV interiors
Graphene–Polymer	Moderate	Structural + Conductive	65	High	Battery casings
BN–Epoxy	Moderate	Thermal + Electrical	50	High	Heat spreaders
Smart Aerogel	Low–Medium	EMI + Flame + Sensor	70	Excellent	Battery rescue systems
Recycled PET–CNT	High	Lightweight + Shielding	55	Moderate	Dashboard and enclosure
Bio-epoxy/Nano SiC	High	Thermal + Sustainable	45	High	Battery enclosure shells

Sustainability, Safety, and Multifunctionality Integration

Sustainability and safety are the underlying themes driving material and system design in modern EVs. Singh et al. [22] and Dobrotă et al. [3] underscored the use of biopolymers and recyclable composites, which align with global carbon-neutral objectives. Meanwhile, Wang et al. [27] and Zhang et al. [28] introduced smart sensing composites that perform multiple functions—heat regulation, fault detection, EMI shielding, and flame resistance—creating a unified design philosophy.

From an industrial perspective, these findings suggest that the most suitable EV materials are not always those with the highest peak performance, but those that provide the best compromise among thermal stability, manufacturability, recyclability, cost, and multifunctional integration. This table illustrates that multifunctional composites are evolving toward smart-sustainable hybrids—materials that combine recyclability with sensor integration and protective functionalities. However, challenges persist regarding cost, mass production, and environmental degradation resistance, requiring further industrial research.

Analytical Insights

The combined findings reveal that EV innovation now rests on three interdependent pillars:

1. *Advanced composites:* Materials are evolving from single-function load-bearers to multifunctional, thermally intelligent structures.
2. *AI-Augmented BTMS:* Intelligent systems provide adaptive, real-time heat regulation with predictive fault prevention.
3. *Sustainability Integration:* Green polymers and recyclable composites ensure environmental responsibility without compromising performance.

Overall, graphene- and BN-based composites remain dominant for high thermal conductivity, while bio-based polymers gain traction in sustainable manufacturing. On the control side, deep learning and reinforcement learning models have achieved industrial maturity, offering enhanced predictive accuracy and adaptability. The convergence of these technologies results in smart, energy-efficient, and safe EV architectures, where the material and control systems operate synergistically.

Future advancements will focus on integrating embedded sensors within composites, allowing direct thermal feedback to AI controllers, thereby creating a closed-loop intelligent EV system. The reviewed studies collectively establish that combining material intelligence with computational intelligence is the most viable pathway to achieving scalable, sustainable, and next-generation electric mobility.

Despite the valuable insights obtained from the reviewed studies, certain limitations should be acknowledged. First, the performance values reported across different works are not always directly comparable because they depend on differences in material composition, test conditions, battery formats, cooling configurations, modeling assumptions, and evaluation metrics. Second, many studies remain at laboratory or simulation scale, whereas industrial validation under real-world EV operating environments is still limited. Third, AI-based thermal management studies often rely on specific datasets and system configurations, which may affect the generalizability of prediction accuracy and control performance. Therefore, although the overall trends are technically meaningful, the results should be interpreted as comparative indicators rather than universally standardized benchmarks.

The graphical results corresponding to Figures 1–7 should be inserted in the final manuscript immediately after the discussion of Tables 5–8 so that the visual comparisons directly support the analytical interpretation presented in this section. To strengthen the comparative interpretation of the reviewed studies, seven analytical figures are included to visualize the relationships among material properties, cooling performance, prediction accuracy, energy savings, and sustainability indicators. These figures are intended to complement the tabulated comparisons and provide a clearer representation of the interdependence between composite design, thermal regulation, and intelligent control in EV systems.

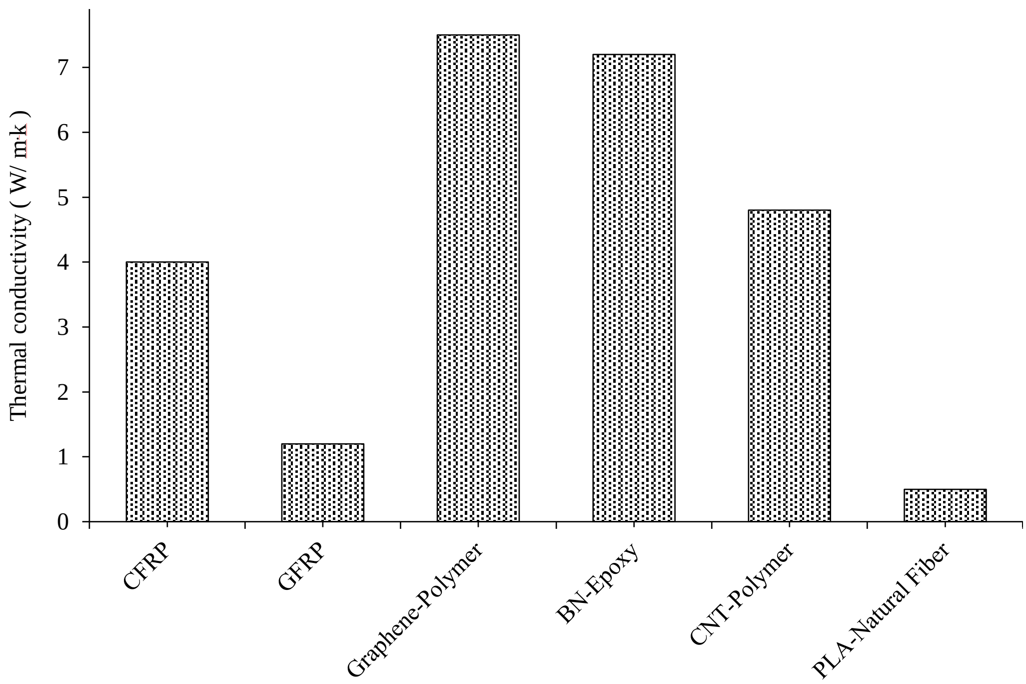

Figure 1. Thermal conductivity of different polymer composites.

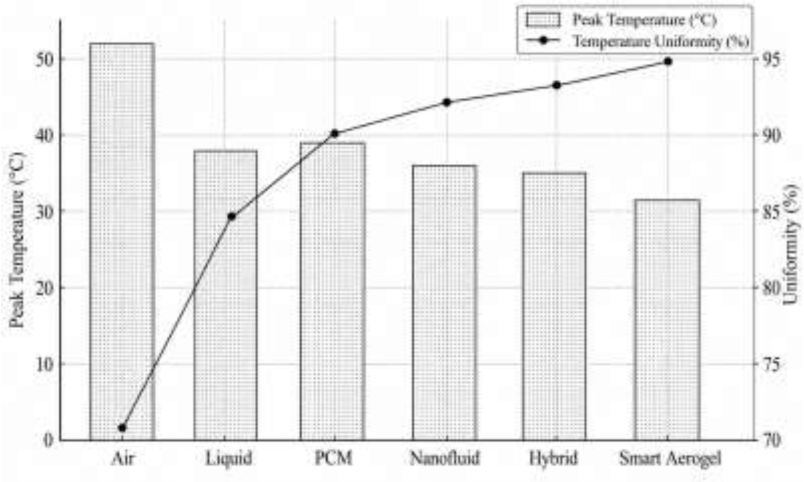

Figure 2. Thermal performance of thermal management methods.

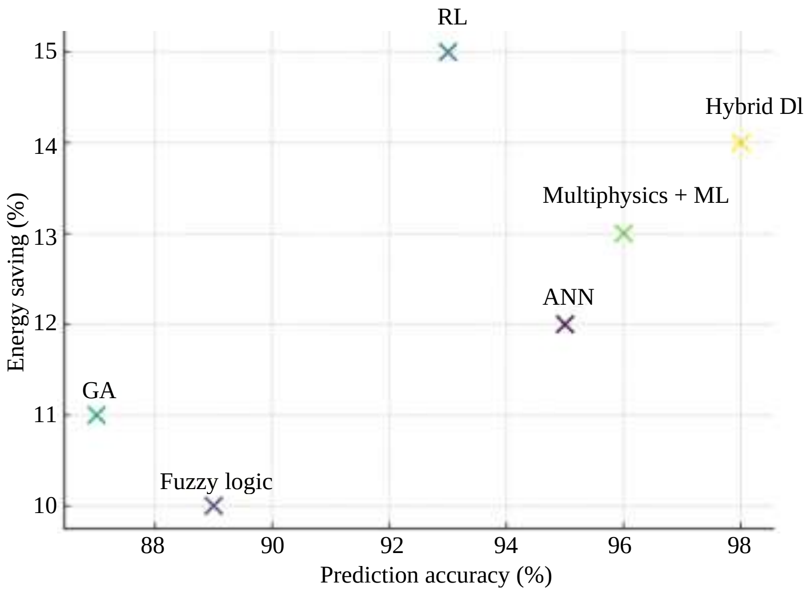

Figure 3. Analysis of the performance of AI techniques.

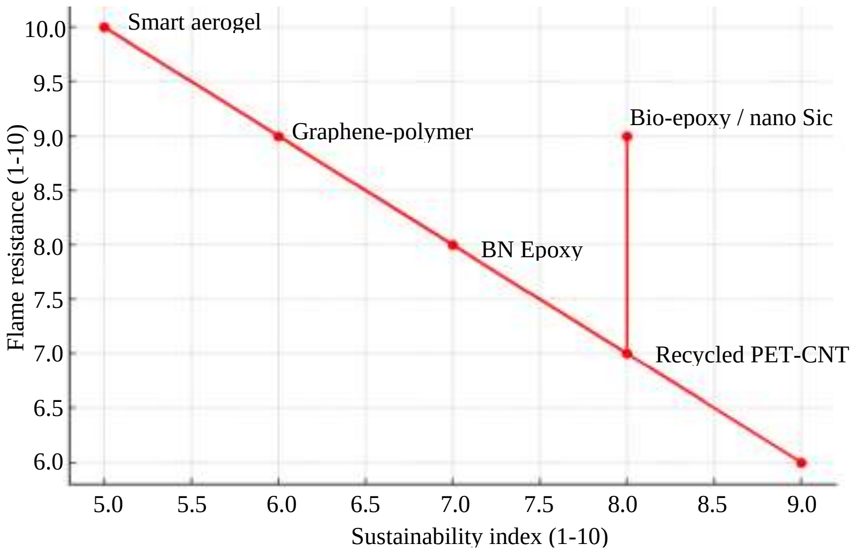

Figure 4. Sustainability flame resistance composites.

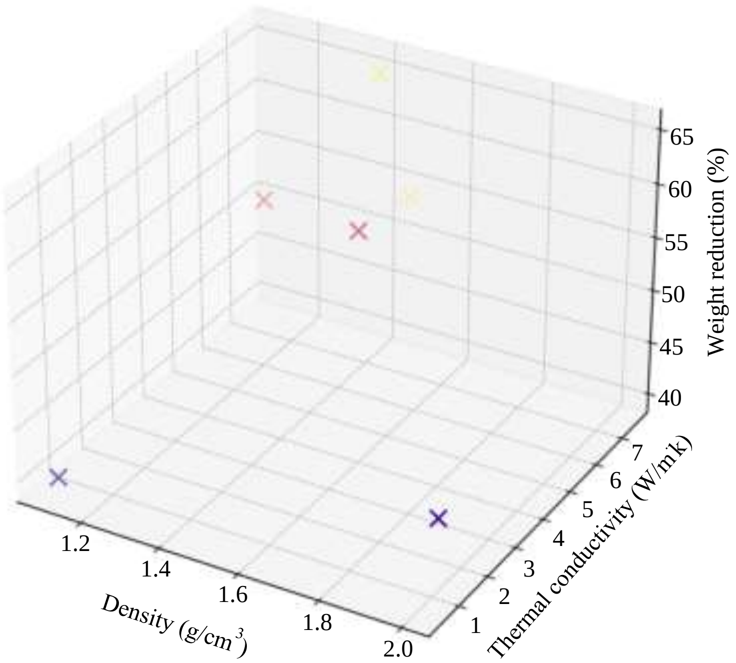

Figure 5. Composite material properties 3D analysis.

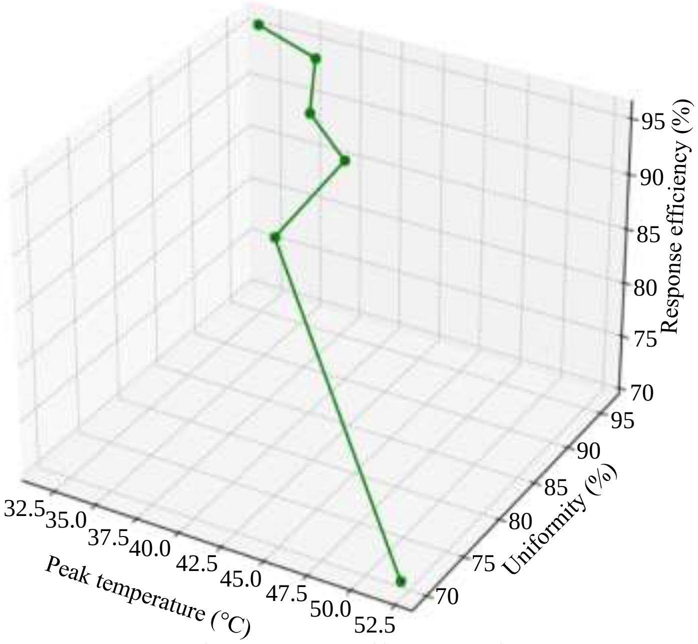

Figure 6. Analysis of 3D cooling efficiency of BTMS methods.

Figures 1–7 collectively illustrate the strong interdependence between material design, thermal regulation, and intelligent control in EV systems. Figures 1, 4, and 5 show that graphene-, boron nitride-, and CNT-based polymer composites provide a favorable balance of low density, high thermal conductivity, and significant weight reduction, whereas bio-based composites offer stronger sustainability benefits but comparatively lower thermal performance. Figures 2 and 6 indicate that hybrid cooling strategies, particularly PCM–liquid and smart aerogel-assisted systems, achieve lower peak temperatures and greater temperature uniformity than conventional air-cooling approaches. Figures 3 and 7 further demonstrate that AI-based BTMS strategies with higher prediction accuracy generally deliver improved energy savings and more adaptive thermal control, especially in

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reinforcement learning, hybrid deep learning, and multiphysics-assisted machine learning frameworks. Together, these figures support the conclusion that high-performance multifunctional composites and intelligent thermal control systems are converging toward an integrated EV design paradigm focused on lightweighting, safety, energy efficiency, and sustainability. This number is a comparison of the thermal conductivity in the six most popular polymer composite systems: C FRP, GFRP, Graphene-Polymer, BN-Epoxy, CNT-Polymer and PLA-Natural Fiber. The bar graph shows a strong hierarchy of thermal performance with graphene and the boron nitride-based composites having a better thermal performance (about 7–8 W/m·K) because of the crystalline filler networks, which allow the conductance of phonons. Conversely, conventional glass fiber and PLA-natural composites exhibit low conductivity (less than 1.5 W/m·K), so could be used as insulation or structural components instead of active thermal control. The plot highlights that hybrid fillers, in particular, graphene and BN, are multi-functional, as they can be used to enhance mechanical strength and at the same time create effective heat transfer. This directly corresponds to EV requirements of thermo stable and lightweight enclosures, battery cases and power electronic cases.

The 3D plot shows the association that exists between peak temperature, uniformity, and reaction efficiency of distinct cooling strategies. The increasing trend is that the greater the uniformity of temperature, the greater the responsiveness, and low temperatures are. Smart aerogel and hybrid PCM liquid systems are clustered around the optimal range with the lowest thermal extremes (~32 ^{o}C) and highest response efficiency (>95%). The bottom of the list is taken by air and liquid cooling options because of the slower dynamic adaptation. The figure stresses that material-based BTMS improvements with responsive control attain excellent thermal performance. It graphically validates the fact that hybrid and smart material-based cooling frameworks offer a breaking edge in the case of long-term EV performance. Figure 7 examines the linear relationship between accuracy of AI models and energy saving. The regression trend (red dashed line) shows that the linearity is very positive- the greater the predictive accuracy, the greater will be the energy conservation in BTMS. The slope demonstrates that an increase in the accuracy of the model by 1% may result in an increase in the additional energy efficiency by about 0.80 to 1%. Hybrid deep learning, reinforced learning, and multiphysics models are found in the upper-right quadrant, which proves their supremacy in adaptive control. This connection supports the value of data quality, model interpretability, and ongoing training in order to achieve the highest level of operational efficiency. The observation also confirms the fact that AI-based BTMS improves cooling efficiency in addition to minimizing auxiliary energy consumption, which increases general driving range. All these seven figures together create a coherent image of the technological development of EV materials and control systems. Figures 1, 4, and 5 concentrate on the material science dimension and show that the design of composite determines the physical and environmental characteristics.

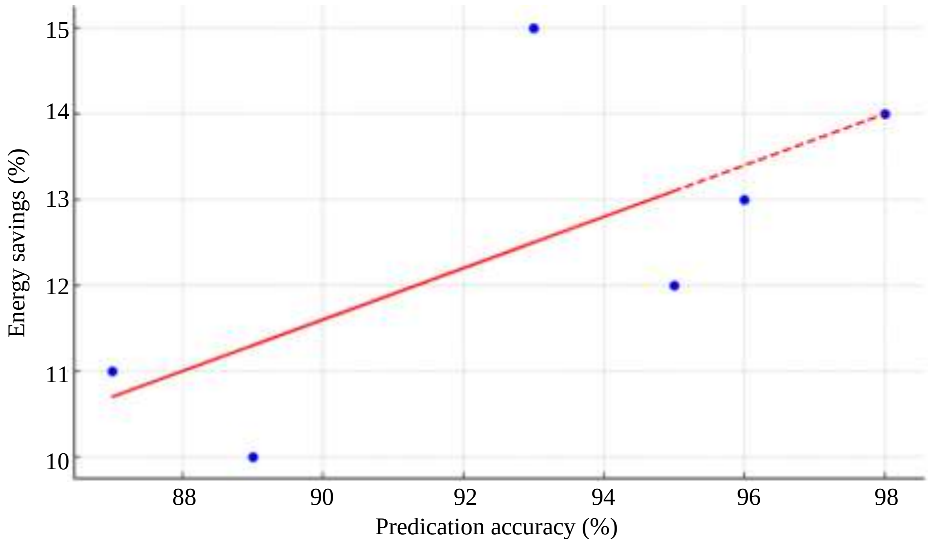

Figure 7. Relationship between AI prediction accuracy and energy efficiency.

Figures 2, 3, and 6 cover the thermal and computational aspect, demonstrating the excellence of the AI-based and material-integrated cooling mechanism.These two arenas are bridged in Figure 7, which demonstrates that accuracy in artificial intelligence prediction has a direct translation to actual energy and thermal benefits. Collectively, the reviews confirm an important trend the merging of high-tech polymer composites with smart, adaptable BTMS structures is reinventing the future of electric mobility, providing lighter, safer, and more energy efficient vehicles with built-in intelligence both at the material and system scales.

MANUFACTURING SCALABILITY, COST–PERFORMANCE TRADE-OFF, AND INDUSTRIAL ADOPTION CHALLENGES

While multifunctional polymer composites and AI-based battery thermal management systems have demonstrated substantial potential for electric vehicle applications, their widespread industrial implementation still faces important manufacturing and economic barriers. From a materials perspective, high-performance composites such as carbon-fiber-reinforced polymers, graphene-reinforced polymers, boron nitride-filled epoxies, and carbon nanotube-based systems offer superior specific strength, thermal conductivity, and multifunctionality; however, these benefits are often associated with high raw material cost, complex processing requirements, and limited throughput in large-scale automotive production. For example, carbon fiber composites provide excellent stiffness-to-weight ratios, but their manufacturing often depends on energy-intensive curing cycles, precision lay-up, and costly tooling. Similarly, graphene- and CNT-based composites exhibit highly attractive thermal and electrical properties, yet their industrial deployment is constrained by difficulties in uniform filler dispersion, interfacial adhesion control, reproducibility, and quality assurance during mass production.

In addition, the selection of a composite for EV structures cannot be based only on laboratory-scale performance. Automotive manufacturers must evaluate process scalability, repairability, recyclability, joining compatibility, production cycle time, and supply chain reliability. Glass-fiber-reinforced polymers are comparatively more economical and easier to manufacture than carbon-fiber systems, but they provide lower mechanical and thermal performance. Bio-based and natural-fiber composites are promising from a sustainability viewpoint, though they still require improvements in moisture resistance, thermal endurance, and durability under long-term service conditions. Therefore, an industrially viable material platform must balance weight reduction, thermal performance, cost, manufacturability, and environmental impact rather than maximizing only one property.

A similar trade-off exists in AI-enabled battery thermal management. Advanced machine learning and deep learning models can improve temperature prediction, fault diagnosis, and adaptive cooling control, but their real-world use depends on computational efficiency, sensor reliability, explainability, and integration with embedded vehicle electronics. Highly accurate deep models may require large datasets, frequent retraining, and greater computational resources, whereas simpler models such as fuzzy logic or support vector regression may be easier to deploy but may offer lower adaptability in highly dynamic operating conditions. For EV manufacturers, the preferred BTMS solution is therefore not necessarily the most complex algorithm, but the one that achieves robust thermal control with low computational overhead, real-time responsiveness, and compatibility with production battery management systems.

Overall, the future industrial success of these technologies depends on co-optimization across material design, manufacturing route, system cost, and control intelligence. Scalable fabrication methods, standardized testing protocols, cost-effective nanofiller dispersion techniques, recyclable composite architectures, and lightweight AI models suitable for embedded deployment will be essential. Thus, the transition from research prototypes to commercially viable EV systems requires a practical engineering framework in which material innovation and intelligent thermal control are evaluated not only by performance enhancement, but also by manufacturing feasibility and total lifecycle value.

CONCLUSION

This review has critically examined the emerging convergence between multifunctional polymer composites and artificial intelligence-driven battery thermal management systems as two of the most influential enablers of next-generation electric vehicles. The analysis demonstrates that these domains are not developing in isolation; rather, they are increasingly forming an integrated design framework in which lightweight structures, thermal regulation, energy efficiency, operational safety, and sustainability are addressed simultaneously.

From the materials perspective, polymer composites reinforced with carbon fiber, graphene, boron nitride, carbon nanotubes, and related nanostructured fillers offer a highly attractive combination of low density, high specific strength, corrosion resistance, and enhanced thermal functionality. Compared with conventional metallic materials, these composites can significantly reduce structural mass while also enabling additional roles such as electromagnetic shielding, passive heat dissipation, flame resistance, and smart sensing. Their growing use in chassis members, battery enclosures, protective housings, and thermal interface structures shows that polymer composites are evolving from passive structural materials into multifunctional engineering platforms for advanced EV applications.

From the thermal management perspective, the review confirms that AI-based BTMS has introduced a clear transition from passive and reactive cooling strategies toward predictive, adaptive, and data-driven thermal regulation. Machine learning, deep learning, fuzzy logic, support vector regression, and reinforcement learning techniques are increasingly being used to forecast battery temperature behavior, detect thermal anomalies, optimize coolant flow, regulate auxiliary cooling components, and reduce parasitic energy losses. When coupled with multiphysics modeling and real-time sensing, these methods provide a more responsive and energy-aware framework for maintaining battery operation within safe and efficient temperature limits.

An important outcome of the reviewed literature is that hybridization offers the greatest performance gains. Thermally conductive composites, phase change materials, nanofluid-assisted cooling, and intelligent control algorithms together produce better temperature uniformity, lower thermal peaks, improved battery life, and greater overall system efficiency than conventional single-mode solutions. In particular, graphene- and boron nitride-based composite systems appear highly promising for thermal-interface and enclosure applications, while AI-enhanced hybrid cooling strategies show strong potential for practical EV battery modules operating under variable load and charging conditions.

The review also highlights a broader shift toward multifunctionality and embedded intelligence. Composite materials are increasingly being designed not only for load-bearing and heat transfer, but also for sensing, self-heating, fault indication, and system-level interaction with digital controllers. This trend suggests that future EV platforms may employ smart material systems capable of directly feeding thermal and structural information into AI algorithms, thereby enabling closed-loop, self-aware battery safety and performance management architectures.

At the same time, industrial adoption still depends on solving important practical challenges. High-performance nanocomposites often face barriers related to cost, filler dispersion, manufacturability, reproducibility, repairability, and recyclability. Similarly, advanced AI models must satisfy real-world constraints involving sensor reliability, computational efficiency, explainability, embedded implementation, and long-term robustness under dynamic driving environments. Therefore, the most viable future solutions will be those that achieve balanced co-optimization across material performance, manufacturing scalability, lifecycle sustainability, and intelligent control capability.
Overall, the review establishes that the combined advancement of multifunctional polymer composites and AI-driven thermal management represents a compelling pathway toward lighter, safer, more energy-efficient, and environmentally responsible electric vehicles. Future research should focus on scalable manufacturing of multifunctional nanocomposites, standardized testing protocols, recyclable

composite architectures, embedded sensing integration, and lightweight interpretable AI models for real-time deployment. The long-term vision is the development of electric vehicles in which material intelligence and computational intelligence work together seamlessly to enhance performance, sustainability, and resilience in modern mobility systems.

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