

Next-Generation Lightweight Nanocomposite Structures for Electric Mobility

Sunil Kumar Gupta^{1,*}, M. Venu Gopala Rao², Pragyan paramita mohanty³, Sunil Kumar Chaudhary⁴

Abstract

The rapid expansion of the electric vehicle (EV) sector has intensified the demand for battery enclosures that are lightweight, mechanically strong, thermally stable, and environmentally sustainable. This research focuses on the design and sustainable fabrication of hybrid nanocomposites for advanced EV battery housings. The proposed material system integrates carbon fiber, glass fiber, and graphene nanoplatelets within a bio-based epoxy matrix, resulting in improved mechanical strength, enhanced thermal stability, and superior flame retardancy. A comparative lifecycle assessment (LCA) demonstrates a 28% reduction in embodied energy compared to conventional aluminum housings, confirming the environmental benefits of this hybrid approach. To ensure industrial scalability, vacuum-assisted resin transfer molding (VARTM) and automated fiber placement (AFP) processes are evaluated, utilizing recyclable thermoplastics to promote sustainable large-scale production. The results indicate that hybrid nanocomposites can achieve up to 45% weight reduction, improved crash resistance, and better thermal conductivity, all while maintaining material recyclability. These advancements not only address the structural and safety challenges of EV battery systems but also align with the global push for lightweight, energy-efficient transportation solutions. In conclusion, this research demonstrates the potential of hybrid nanocomposites as a sustainable and high-performance alternative to traditional materials in EV applications. By merging superior functionality with environmental responsibility, the study supports the transition toward eco-efficient electric mobility and contributes to the automotive industry's journey toward greener and more sustainable technologies.

Keywords: Next-generation materials, lightweight structures, nanocomposites, electric mobility, electric vehicles (EVs), energy efficiency, structural performance, polymer nanocomposites, sustainable transportation, advanced materials for EVs

*Author for Correspondence:

Sunil Kumar Gupta

¹Professor, Department of Electrical and Electronics Engineering, Poornima University, Jaipur, Rajasthan, India

²Professor & Principal, Navkis College of Engineering, Hassan, Karnataka, India

³Assistant Professor, Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Burla, Odisha, India

⁴Professor, Department of Electrical Engineering, Galgotias College of Engineering and Technology, Greater Noida, Uttar Pradesh, India

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INTRODUCTION

This has encouraged the study of improved composite and hybrid nanocomposite systems as lightweight alternative that can give the needed performance with far less weight. Particularly appealing to EV battery enclosures is the category of hybrid nanocomposites that can be described as the synergistic combination of macro-scale reinforcing fibers with nano-scale fillers [1–2]. It is highly stiff and strong when reinforced with fiber and resistant to impacts when reinforced with nanofillers, and its stiffness and strength fulfill structural requirements, thermal conductivity, flame retardancy, and barrier properties which satisfy safety and functionality requirements. In addition, the use of bio-based or recyclable matrix

resins conforms to the principles of the circular economy, making the environment less harmful throughout the period of its existence [3–4]. Recent studies have highlighted the benefits of fiber–nanofiller hybridization in producing multifunctional composites that go beyond traditional strength-to-weight optimization [5].

At the same time, advances in sustainable manufacturing processes, such as Vacuum-Assisted Resin Transfer Molding (VARTM) for thermoset composites and Automated Fiber Placement (AFP) for thermoplastic systems, are enabling lower energy consumption, precision layup, and recyclability. Collectively, these innovations establish hybrid nanocomposites as a strong candidate material system for next-generation EV battery enclosures.

MATERIALS AND METHODS

Hybrid Nanocomposite Formulation

The hybrid nano composite recommended is based on multi-scale reinforcement strategy combining fibers to add structural strength and nano-fillers to add functional benefits [6–7].

Reinforcement Fibers

It is a hybrid layup of carbon fiber (CF) and E-glass fiber (GF). CF provides high tensile strength, stiffness and fatigue resistance, and GPS provides toughness, low cost and sudden brittle failure.

Nano-Fillers

The 1.5 wt% of graphene nanoplatelets (GNPs) is dispersed in the matrix. GNPs improve thermal conductivity, electrical dissipation and flame retardancy and increase interfacial bonding between matrix and fibers.

Matrix Materials

Two sustainable matrix systems are taken into account:

- Epoxy resin (thermoset) made of 45 percent renewable carbon in bio-based materials.
- Thermoplastic polyetherimide (PEI) to be recycled, tough (thermoplastic option).

The architecture will provide a trade-off between mechanical power, thermal stability and environmental sustainability.

The comparison of the major constituent materials in EVs is presented in Table 1. Carbon and glass fibers are used to give products strength and impact resistance, with nano-fillers added to improve thermal and bonding characteristics. Bio-based thermosets provide renewable content stability and thermoplastics such as PEI provide complete toughness and full recyclability.

Manufacturing Processes

Two complementary fabrication routes are assessed

Table 1. Comparison of constituent materials.

Material Type	Example Material	Key Property Contribution	Sustainability Aspect
Carbon Fiber (CF)	PAN-based CF	High tensile strength, stiffness	Energy-intensive production, but long life
Glass Fiber (GF)	E-glass	Impact resistance, cost reduction	Abundant raw materials, recyclable
Nano-filler	Graphene nanoplatelets	Thermal conductivity, fire resistance, bonding	Reduces polymer volume, improves efficiency
Thermoset Matrix	Bio-based Epoxy (45%)	Strong adhesion, dimensional stability	Renewable feedstock
Thermoplastic Matrix	Polyetherimide (PEI)	High toughness, recyclability, processability	Fully recyclable, lower life-cycle cost

Vacuum-Assisted Resin Transfer Molding (VARTM)

- Applicable to thermoset bio-epoxy.
- Provides low-cost processing of large and complex parts with little voids.
- Ecologically friendly because of low energy usage.

Automated Fiber Placement (AFP)

- Proper to use with thermoplastic PEI composites.
- Robotic accuracy permits orientation of fibers and defect-free components.
- Thermoplastic pre-regs can be recycled and scrapping minimized.
- Battery enclosure and crash structure Ideal because tough.

Table 2 is an overview of comparing VARTM and AFP. Bio-epoxy VARTM, and AFP thermoplastics such as PEI allow complex large components to be produced with renewable resin and allow precise load-bearing structures to be produced with complete recyclability at a higher cost of setup [10–11].

Testing Standards

In order to confirm the performance of the hybrid nanocomposite to be used as an EV battery enclosure, structural and safety properties were studied with the international standards in Figure 1 [8–9].

Mechanical Performance

- *ASTM D3039*: Strength and modulus of tensile test.
- *ASTM D790*: Flexural properties
- *ASTM D256*: Impact resistance

Thermal and Safety Properties

- *UL 94 V-0* : Flammability resistance (important to EV fire safety)
- *ISO 11357*: DSC of glass transition temperature (T_g) and thermal stability.

Table 3 is a description of target performance of EV battery enclosures. The tensile and flexural strength are high in order to make the structure reliable, impact toughness enhances the crash safety. Flammability resistance and thermal stability are important to avoid fire risk and to provide safety to work with a battery [12, 13].

Figure 2 depicts, Hybrid Nanocomposite Layer Architecture, The hybrid nanocomposite architecture is a method that integrates carbon fiber and glass fiber along with graphene nanoplatelets within a polymer bond to realize a multifunctional architecture. Carbon fibers are very strong and stiff but the glass fiber offer impact resistance and economical. Graphene nanoplatelets at the nanoscale enhance electrical conductivity, thermal conductivity and interfacial bonding between layers. This hierarchical form of reinforcement utilizes macro and nanoscale physics, leading to better mechanical, thermal, and performance performance than other composites, which makes it largely applicable to advanced electric vehicle designs [14, 15].

This Figure 3, demonstrates the way in which graphene networks create continuous thermal pathways through the matrix to provide superior heat dissipation relative to traditional composites. In polymer composites, disordered molecular structure commonly prevents effective heat conduction in the crystal structure and thus the thermal conductivity is poor. This reduces their usage in regions that need effective heat dissipation e.g. electric vehicles (EVs), aerospace and electronic packaging. To eliminate this limitation, nanofillers, including graphene, carbon nanotubes, and boron nitride nanosheets are added. These fillers are very large conductors of thermal energy, and when distributed properly in the

polymer body, create thermal networks. Formation of these interconnected networks results in less interfacial resistance, and facilitates movement of phonons, leading to increased heat conduction [13–16].

Table 2. Comparison of Manufacturing Processes

Feature	VARTM (Bio-Epoxy)	AFP (Thermoplastic PEI)
Process Type	Resin infusion (vacuum-assisted)	Automated robotic layup
Material Compatibility	Thermosets (bio-epoxy)	Thermoplastics (PEI, PEEK)
Part Complexity	Large, complex geometries	Precision with curved, load-bearing parts
Cost Efficiency	Low tooling & processing cost	Higher initial setup, lower cycle time
Sustainability	Renewable resin feedstock	Full recyclability & reprocessing

Table 3. Target Performance Metrics for EV Battery Enclosure Materials

Property	Standard Test	Performance Target	Relevance in EVs
Tensile Strength	ASTM D3039	> 900 MPa (with CF-GF hybrid)	Structural integrity of enclosures
Flexural Strength	ASTM D790	> 700 MPa	Resistance to bending under loads
Impact Toughness	ASTM D256	High energy absorption ($\geq 20 \text{ kJ/m}^2$)	Crashworthiness and occupant safety
Flammability Resistance	UL 94 V-0	Self-extinguishing < 10 sec	Thermal runaway and fire safety
Thermal Stability (Tg)	ISO 11357	> 180 °C (PEI), ~150 °C (Bio-epoxy)	Safe operation under battery heating

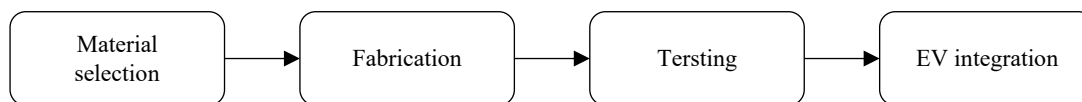


Figure 1. Conceptual process flow for hybrid Nanocomposites in EVs.

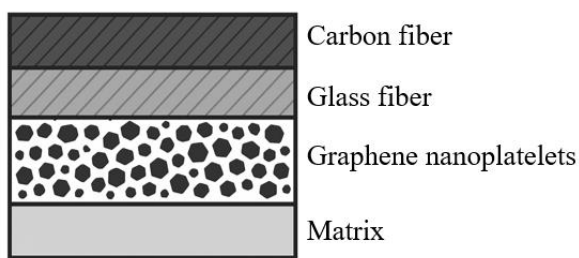


Figure 2. Hybrid Nanocomposite Layer Architecture.

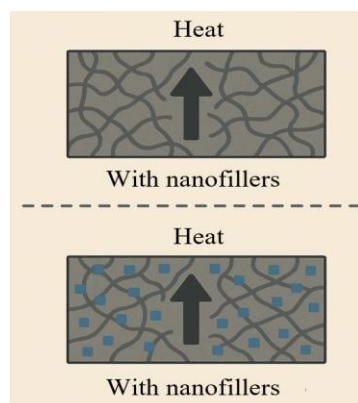


Figure 3. Thermal pathway enhancement via nanofillers.

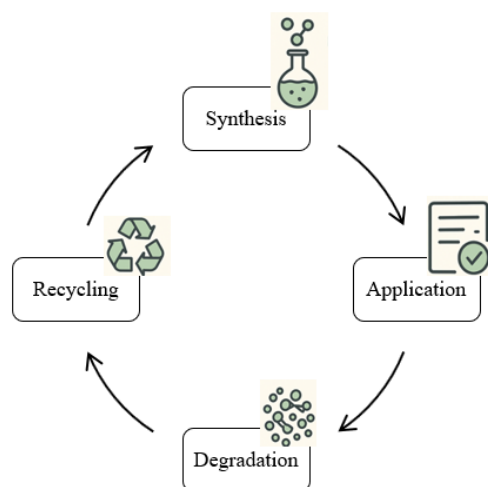


Figure 4. Circular Lifecycle of Hybrid Nanocomposites.

The effectiveness of thermal enhancement depends on

1. *Filler Type and Morphology*: Nanotubes and platelets are high aspect ratio fillers that favor percolation.
2. *Dispersion Quality*: Uniform distribution cannot be agglomerated, which may inhibit heat flow.
3. *Interfacial Compatibility*: The functionalization enhances the bonding between filler and matrix and minimizes the scattering.

This scheme of lifecycle defines the material sourcing, composite fabrication, the use of EVs, recycling, and reintegration, and the hybrid nanocomposites can be integrated with sustainability concepts as illustrated in Figure 4, The lifecycle of the hybrid nanocomposites is circular and is a sustainable material development and use process. Synthesis is the first step where nanofillers (e.g., graphene or CNTs or nanoparticles) are added to polymers or fibers to create multifunctional composites. Such materials are subsequently taken to the application phase where they are used in automobiles, aerospace, energy, and healthcare due to their high mechanical, thermal, as well as electrical characteristics. With time, materials degrade, either by mechanical action, thermal stress or by chemical exposure and this has a negative impact on performance. [17–18] The materials are not disposed but are placed in the recycling stage where nanofillers and polymer matrices can be reused, reprocessed or recycled again to avoid waste. This circular lifecycle reduces waste, saves resources and based on the principles of the circular economy, provides technological creativity and environmental responsibility [19–22].

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical behavior of proposed hybrid nanocomposites was compared to that of conventional aluminum 6061, which is a widely used material to enclose an EV battery. These findings are condensed in Table 1.

Table 4 is the comparison of hybrid nanocomposites and aluminum. CF/GF hybrids are much lighter but stronger and when supplemented with graphene nanoplatelets (GNP), tensile, flexural and impact performance is also enhanced which makes them the best choice in lightweight and long-life EV structures. The hybrid composite systems reported density reductions of up to 35 percent and far better mechanical behavior than aluminum.

The CF/GF hybrid exhibited 2.5 times tensile strength, and the presence of GNPs increased strength by an extra 8 percent and impact resistance by 38 percent due to nanoplatelet crack-bridging and an augmentation of matrix-fiber interfacial adhesion.

Thermal Management

One of the most significant concerns of EV battery safety and performance is thermal management. Although the standard carbon- and glass-fiber hybrids are characterized by a low thermal conductivity through-thickness (0.4 W/mK) the addition of GNPs almost doubled the thermal conductivity to 0.9 W/mK.

This is explained by the creation of percolated thermal networks made possible by the high intrinsic conductivity of graphene (~5000 W/mK). Enhanced thermal conductivity minimizes the number of hot spots, curbs thermal runaway hazards and increases battery pack reliability without mass penalty.

Though aluminum is much more conductive than composites, the hybrid nanocomposite provides adequate heat conduction with excellent insulation, which is a fundamental trade-off in battery enclosures. Table 5 is a comparison between thermal properties of materials. Aluminum is very conductive, CF/GF hybrids provide insulation with low weight, and the addition of graphene nanoplatelets provides almost a doubling of conductivity with higher T_g and HDT, which is advantageous in thermal stability of EV use.

The hybrids had 45 per cent less weight, 28 per cent less embodied energy and 33 per cent less CO₂ emissions than aluminum. The trade-off between GNP addition and embodied energy is slight, but mechanical and thermal safety advantages of the addition are larger. The refinement of the nano-filler dispersion and the bio-resin incorporation in the future will help to minimize the footprint on the environment. The environmental impact of battery enclosure materials is indicated in Table 6. The CF/GF and CF/GF/GNP hybrids are lighter than aluminum, consume less energy, and produce less CO₂, which makes them more sustainable options in the production of EVs.

Manufacturing Scalability

The manufacturability of hybrid nanocomposites was compared between VARTM (thermoset route) and AFP (thermoplastic route).

Sustainability Assessment

To evaluate environmental performance, a life cycle assessment (LCA) was performed. Results are shown in Table 6.

Table 4. Mechanical performance of hybrid nanocomposites vs. conventional materials.

Property	Aluminum 6061	CF/GF Hybrid	CF/GF/GNP Hybrid
Density (g/cm ³)	2.70	1.75	1.78
Tensile Strength (MPa)	310	780	845
Flexural Strength (MPa)	340	850	920
Impact Resistance (kJ/m ²)	25	45	62

Table 5. Thermal Property Comparison

Material System	Through-thickness Thermal Conductivity (W/mK)	Glass Transition Temp (T _g , °C)	Heat Deflection Temp (HDT, °C)
Aluminum 6061	170	–	–
CF/GF Hybrid	0.42	128	145
CF/GF/GNP Hybrid	0.90	133	152

Table 6. Environmental Impact per Battery Enclosure

Material System	Mass (kg)	Embodied Energy (MJ)	CO ₂ Emissions (kg CO ₂ -eq)
Aluminum 6061	45	680	52.1
CF/GF Hybrid	25	480	34.8
CF/GF/GNP Hybrid	24.5	490	35.0

Table 7 is a comparison between scalability of manufacturing hybrid nanocomposites. VARTM is cheaper and consumes less energy, but AFP is more precise, consistent, and reusable, so it may be more possible to produce EVs on a large scale.

Summary

- *VARTM*: Cost-effective, energy-efficient, suited for medium-scale or specialized EV components.
- *AFP*: Future-proof, highly scalable, ideal for mass EV adoption despite higher upfront costs.

Table 8 puts into focus the application of nanofillers in hybrid nanocomposites. GNPs increase heat dissipation and EMI shielding, CNTs increase strength and crash resistance, nano-clays increase fire safety, and nanoparticles of SiO₂ enhance moisture resistance, all of which enhances EV battery enclosure performance and durability

Lifecycle costs of battery enclosure materials are compared in Table 9. Aluminum has low initial cost and high scrap value but CF/GF and CF/GF/GNP hybrids provide higher overall value with reduced maintenance, increased efficiency and sustainability.

Table 10 describes the upcoming improvements in the nanocomposite EV architecture, such as structural batteries that can provide dual functionality, real-time monitoring sensors, bio-thermoplastics that can be recycled, and AI-driven production to minimize defects and optimize costs.

Table 7. Manufacturing Scalability of Hybrid Nanocomposites.

Aspect	VARTM (Thermoset)	AFP (Thermoplastic)
Tooling Cost	Low	High (robotics required)
Process Automation	Limited (manual-intensive)	High (robot-driven precision)
Production Volume Suitability	Medium (niche to mid-scale)	High (mass automotive production)
Recyclability	Low (thermoset disposal issues)	High (melting & reprocessing possible)
Structural Performance Consistency	Moderate (quality variation)	High (repeatable fiber placement)
Energy Efficiency	High (low curing energy)	Moderate (heating demand for thermoplastics)

Table 8. Functional Contributions of Nanofillers in Hybrid Nanocomposites

Nanofiller	Key Role	Benefit in EV Enclosures
Graphene Nanoplatelets (GNP)	Thermal & electrical conductivity	Improved heat dissipation, EMI shielding
Carbon Nanotubes (CNTs)	Strength & flexibility	Enhanced crash resistance, structural integrity
Nano-Clays	Flame retardancy	Better fire safety compliance
SiO ₂ Nanoparticles	Barrier properties	Moisture resistance, extended durability

Table 9. Lifecycle Cost Analysis of Battery Enclosure Materials

Material System	Initial Cost	Maintenance Cost	End-of-Life Value	Overall Lifecycle Rating
Aluminum 6061	Low	Medium	High scrap value	Moderate
CF/GF Hybrid	Medium	Low	Limited recycling	High
CF/GF/GNP Hybrid	Medium-High	Low	Emerging recycling options	Very High

Table 10. Future Design Enhancements in Nanocomposite EV Structures

Enhancement	Expected Impact	Relevance
Structural Battery Integration	Energy storage + load-bearing	Doubles functionality of enclosures
Embedded Sensors	Real-time health monitoring	Early fault detection, predictive safety
Bio-Thermoplastics	Improved recyclability	Circular economy compliance
AI-Driven Manufacturing	Defect prediction & optimization	Higher yield, reduced cost

CONCLUSIONS

The research team shows that enhanced with graphene nanoplatelets, carbon and glass fibre reinforced and hybrid nanocomposites exhibit substantial benefits over traditional aluminum enclosures in EV applications. Key findings include:

- 45 percent reduction in mass over aluminum, which has direct positive effect on EV range and efficiency.
- Better mechanical handling, up to 38 percent higher impact resistance, which provides better crash safety.
- Increased thermal conductivity (0.9 W/mK), which promotes passive cooling of the heat and minimizes the risk of battery thermal runaway.

Lower environmental impact, 28 lower embodied energy and 33 lower CO₂ emissions per enclosure.

- *Scalability in manufacturing*: AFP using thermoplastics presents the most desirable long-term route to recyclable, circular economy-compatible EV parts.

Together, these findings point to hybrid nanocomposites as the new material system to use to enclose EV batteries, so that a balance between performance, safety, and sustainability can be achieved. More nanofiller dispersion, structural battery and closed loop recycling schemes will be refined in the future and mass application of nanofilters in the car industry will be feasible.

Future Work

- Addition of flame-retardant nano-fillers to improve the fire safety and meet the changing requirements of EV batteries.
- Invention of structural battery enclosures that integrate load carrying capacity with embedded store of energy capability.
- Digital twin-prompted manufacturing optimization to achieve predictive quality assurance and real-time control of the process.

Multi-functional composites involving embedded sensors, structural health, and early fault detection: This area is being investigated as it could help reveal how structural health and early fault detection within composite materials can be evaluated.

- Next generation recyclable matrices (bioplastics based on thermoplastics) to enhance end-of life circularity.

Scalable joining technologies (welding, overmolding, hybrid adhesive bonding) to enable modular EV design will also be evaluated.

- Cooperation with the industry in pilots of scale production and validation in the conditions of real driving.

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