

Application of Composite Material in Advanced Manufacturing Technology

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ABSTRACT

Due to the fact that they offer significant benefits, including weight reduction, fuel economy, safety, and design freedom, composite materials have become a leading enabler in automotive engineering development. From body parts to structural members, materials such as carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers (GFRP), and natural fiber composites are extensively utilized in automotive components. The need for composites in reducing emissions of carbon and enhancing vehicle performance is also accentuated by the rising focus on electric vehicles (EVs) and green sustainability in the automotive sector. Despite the advantages, there are still barriers to the extensive application of composites to the automobile sector, such as their expensive manufacture, recycling difficulties, and complex fabrication processes. The current applications of composites in the automotive field, the related manufacturing processes, the challenges faced, and the future potential for the development of composite materials for automotive engineering are all analyzed in this research.

1. INTRODUCTION

The automobile industry has experienced a paradigm shift over the past few decades towards the utilization of stronger, lighter, and more energy-efficient materials. Composite materials have emerged as a revolutionary group of materials among these developments, offering significant advantages over conventional metals such as steel and aluminum, particularly regarding weight savings, corrosion resistance, fuel economy, crashworthiness, and design freedom [1]. These advanced materials are increasingly replacing traditional materials in structural and semi-structural components across modern vehicle platforms. They are typically composed of a polymeric matrix with high-strength fibers (carbon, glass, or natural). The necessity to reduce vehicle weight, enhance crashworthiness, and meet more stringent global fuel economy and emissions regulations is the prime motivator for composite materials in automotive engineering. One key strategy here is lightweighting. A 10% reduction in weight of the vehicle is said to yield a corresponding increase in the range for EVs and a 6–8% increase in fuel efficiency for ICE vehicles [2], [3]. Performance and energy efficiency are improved, and life-cycle effect minimization and environmental sustainability are also significantly facilitated by this. Glass fiber reinforced polymers (GFRPs) and carbon fiber reinforced polymers (CFRPs) are the most widely utilized synthetic composites in the automobile field. CFRPs are ideal for structural components of high-performance vehicles due to their excellent mechanical strength and high stiffness-to-weight ratio. GFRPs are less expensive and used more broadly in non-structural or semi-structural parts such as bumpers, hoods, and interior modules, but they have lower strength compared to CFRPs [4]. Due to their biodegradability, low environmental footprint, and cost-effectiveness, natural fiber composites (NFCs) made of fibers such as hemp, flax, and jute are gaining attention as eco-friendly alternatives [5]. Body panels, roof structures, bumper beams, suspension arms, door modules, seat frames, and energy-absorbing crash structures are a few among the numerous auto parts that utilize these composites. Lighter vehicle weight and improved safety for passengers are highly facilitated by their ability to dissipate impact energy without loss of structural integrity [6]. But even with these advantages, several important challenges stand in the way of extensive utilization of composite materials for traditional automobile production. These are long production cycle

durations, special joining and repair needs, reduced recycling routes (yan especially thermoset-based composites), and high raw material and processing prices [7]. In addition, application of high-performance composites such as CFRPs is often limited to premium or high-performance car models due to the cost-sensitive character of high-volume automobile manufacture. One of the greatest challenges for OEMs (Original Equipment Manufacturers) is being able to scale up composite integration without compromising on price or manufacturability. The aims of this study are to provide a comprehensive review of the present applications of composite materials in the automobile industry, consider key manufacturing processes, discuss the economic and technological challenges to increased use, and examine potential future trends, especially concerning electrification, circular material systems, and Industry 4.0-facilitated digital manufacturing.

2. LITERATURE REVIEW

The demand for lighter, safer, and more efficient vehicles has seen a considerable amount of research into the use of composite materials within the automotive industry over the past three decades. Composites were initially developed for aerospace and high-performance applications, but due to their high specific strength, corrosion resistance, and capability to reduce the weight of the vehicle as a whole, they have increasingly found their way into the mass automobile industry. As green replacements for traditional synthetic reinforcements, Bledzki and Gassan [1] were the pioneering researchers to explore the potential of natural fiber-reinforced composites in engineering applications. With a focus on the mechanical advantages of carbon and glass fiber systems and their growing importance in vehicle structural design, Mallick [2] presented a comprehensive overview of fiber-reinforced composites. With the automobile sector going in the direction of electric vehicles (EVs) and low-emission transport, lightweight materials have grown increasingly vital. The U.S. Department of Energy [3] asserts that employing lightweight composites has the potential to significantly reduce fuel consumption and emissions; for instance, a 10% reduction in vehicle weight can lead to an 8% improvement in fuel efficiency. As stated by Friedrich and Breuer [4], carbon fiber reinforced polymers (CFRPs) are some of the composite materials that exhibit excellent mechanical stiffness and strength, yet due to their high material and production costs, they are often applied in just luxury and high-performance automobiles. Even though they are weaker, glass fiber reinforced polymers (GFRPs) are cheaper and most commonly used in semi-structural vehicle components such as engine covers, dashboards, and bumpers [5]. On the other hand, due to their low weight and biodegradability, Natural Fiber Composites (NFCs), such as hemp, flax, and jute, have gained popularity in interior and non-structural uses. Their performance in high-stress uses is, however, limited by their weaknesses in fiber-matrix bonding and moisture resistance, as indicated by studies by Mohanty et al. [6] and Sapuan and Ilyas [7]. Production processes facilitating mass production of composite automobile components have also gained significant attention in recent literature. These include compression molding, resin transfer molding (RTM), and sheet molding compounds (SMC), which are commonly employed. Thermoplastic processing methods are also being researched for their recyclability. When selecting an approach, Gay [8] emphasized finding a balance between cycle time, cost, and mechanical performance. Krüger et al. [9] have highlighted high-pressure RTM (HP-RTM) as a promising process for efficient production of structural composites through the combination of quick throughput with fiber alignment control and high surface quality. Despite these advances, the literature continues to recognize several challenges to widespread acceptance. High raw material prices, recyclability issues (especially in the case of thermoset matrices), higher cycle times compared to metals, and the necessity of advanced joining methods to interface composites with metallic components are a few of the primary issues. These cost limitations were brought to light in a cost-benefit analysis by Elfarjani and Alkhedher [10] for high-volume automotive segments. A further obstacle to the use of circular materials in the production of automobiles is

the absence of standardized recycling infrastructure and technical solutions for end-of-life composite recovery, as highlighted by Tong et al. [11] and Ferreira et al. [12]. The creation of bio-based resins, structural battery composites for electric cars, and the incorporation of digital tools like artificial intelligence (AI) and digital twins into composite design and fault detection procedures are examples of recent research that has shifted toward future-focused solutions. Multifunctional composites with capabilities for energy storage as well as weight reduction were studied by Trivedi and Satyanarayana [13]. As in this case, Park and Lee [14] demonstrated that AI-aided image processing could enhance real-time defect detection for the production of automobile composites, paving the way for automated and more reliable quality control systems. Summing up, the study demonstrates that composite materials are a dynamic and rapidly emerging field with tremendous benefits for car engineering. Yet, further research is needed to resolve processing challenges, price constraints, recycling capacity, and life-cycle design for optimally exploiting their potential for mass production and green mobility. These limitations present enormous opportunities for innovation towards the development of next-generation manufacturing technologies and automotive materials.

3. MANUFACTURING METHODS OF AUTOMOTIVE COMPOSITES

While applying composite materials to cars, the choice of manufacturing process significantly contributes to the cost, performance, quality, and scalability of the finished part. One of the most employed processes, Resin Transfer Molding (RTM), is characterized by its ability to produce higher quality parts with precision dimensional control. With RTM, resin is pressurized into dry fiber preforms that are positioned within a closed mold. It is commonly used for structural body panels and is well-suited for medium-volume production. Compression molding is another popular technique in the manufacture of automobiles, especially when using Sheet Molding Compounds (SMC) and Bulk Molding Compounds (BMC). The technique is highly reproducible and has short cycle times through the compression of a hot composite charge in a cavity mold. It is ideal for manufacturing parts such as bumpers, trunk lids, and hoods in large numbers. Injection molding is often applied to complex geometries and internal parts, typically for short fiber reinforced thermoplastics. It is suitable for high volume applications and enables very rapid production rates, but due to the reduced length of fibers, mechanical properties are affected. Typically applied to high-performance, low-production applications such as sports vehicles and luxury automobiles, autoclave molding consists of heat and pressure curing pre-impregnated fibers (prepregs). It yields superior material properties but at the cost of increased cycle times and an enormous tooling investment. Filament winding and pultrusion find application for continuous and symmetric structures like structural beams or drive shafts. Where linear performance is needed, these processes are applied to ensure optimum fiber alignment. With increasingly advanced digital manufacturing, 3D printing composites is emerging as a mainstream way to make extremely customized, low-volume parts. It has potential for prototype and specialty uses, even with its current restrictions in mechanical performance and manufacturing rate. Trade-offs exist in any industrial process. Production rate, part performance, cost of materials, and tooling investment are all weighed in the automotive industry. Major characteristics of common automobile composites production methods are compared in the table below.

Table: 1 - Comparative Table of Manufacturing Methods

Method	Material Type	Production Volume	Cycle Time	Tooling Cost	Mechanical Strength	Surface Finish	Typical Applications
RTM	Thermoset (Fiber Preform)	Medium	Medium	High	High	Excellent	Body panels, structural supports
Compression Molding	Thermoset (SMC/BMC)	High	Fast	High	Moderate	Good	Fenders, hoods, trunk lids
Injection Molding	Thermoplastic (Short Fiber)	Very High	Very Fast	Moderate	Low–Moderate	Good	Dashboards, door panels, brackets
Autoclave Molding	Thermoset (Prepreg)	Low	Slow	Very High	Very High	Excellent	Roof modules, racing car structures
Filament Winding	Thermoset/Thermoplastic	Medium	Moderate	Moderate	High	Good	Drive shafts, roll bars, cylindrical structures
Pultrusion	Thermoset	Medium–High	Continuous	Moderate	High	Moderate	Beams, structural rails
3D Printing	Thermoplastic/Hybrid	Low	Slow	Low	Low–Moderate	Variable	Prototypes, lightweight brackets

4. COMPARATIVE MECHANICAL PERFORMANCE OF COMPOSITE MATERIALS IN AUTOMOTIVE APPLICATIONS

In the assessment of materials for numerous automotive uses, their mechanical performance is crucial, particularly when balancing durability, weight, and safety. In comparison to traditional metals such as steel and aluminum, composite materials—most notably carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and natural fiber composite (NFCs)—have definite mechanical benefits. Amongst all composite materials, CFRPs possess highest tensile strength and stiffness-to-weight ratio and thus are ideal for high-performance components such as structural shells, battery boxes, and monocoques. Yet, their widespread use in mass-market cars is limited by its exorbitant price and brittleness. GFRPs provide an excellent combination of mechanical strength, impact resistance, and cost despite lacking the stiffness and strength of CFRPs. They are commonly encountered in interior reinforcement, door panels, and bumpers. But NFCs produced from flax, hemp, or jute are valued for their light weight and environmental benefits. Though mechanically low in performance, NFCs are increasingly being used in dashboards, seatbacks, and door trim—especially in scenarios where cost and biodegradability play an important part. Metals such as aluminum and steel are heavier than composites but possess superior recyclability and lower production costs. Steel is not very expensive and is extremely strong, though its weight significantly impacts fuel efficiency. While aluminum is used in most light applications because it weighs less, it lacks composites' tailored mechanical behavior. Hence, material selection in vehicle engineering often involves compromises between sustainability, weight, cost, and mechanical performance.

Table: 2- Comparative Mechanical Properties of Automotive Materials

Material Type	Density (g/cm ³)	Tensile Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)	Impact Resistance	Cost Level	Automotive Applications
CFRP (Epoxy Matrix)	~1.6	800–1500	700–1100	70–120	Low to Moderate	Very High	Structural frames, battery housings, EV shells
GFRP (Polyester Matrix)	~1.9	200–600	250–500	20–40	High	Moderate	Bumpers, trunk lids, body panels
NFC (Flax/Jute + Epoxy)	~1.4	100–300	150–250	5–10	Moderate	Low	Interior trims, dashboards, seat backs
Steel (Mild or HSLA)	~7.8	250–900	200–600	200	High	Low	Chassis, safety cages, engine mounts
Aluminum Alloy (6000 series)	~2.7	250–500	200–350	70	Moderate	Moderate	Wheels, hoods, crash boxes, structural castings

5. MATERIAL SELECTION STRATEGIES IN AUTOMOTIVE COMPOSITE APPLICATIONS

Selecting the correct materials to use for automobile design is a challenging process that is influenced by a variety of factors, such as end-of-life issues, production compatibility, environmental limitations, performance requirements, and cost constraints. Based on the specific component and its function, the selection process for composite materials has to weigh heavily mechanical properties, weight, strength, producibility, and sustainability. Mechanical properties such as tensile strength, stiffness, impact resistance, and thermal stability are prioritized under performance-based selection. CFRP is often applied in structural parts (such as pillars and crash structures) due to its impressive strength-to-weight ratio, although at a higher cost. GFRP offers a cheaper but mechanically sufficient alternative for external and semi-structural panels. Natural fiber composites, such as hemp or jute, are increasingly used for non-load-bearing interior applications due to their visual appeal, biodegradability, and low density.

In material selection, cost-performance compromises are essential. While mass-market cars require GFRP or hybrid composites to be competitive, performance and luxury cars employ CFRP to make their premium prices acceptable. Choices are also driven by factors like material availability, recyclability, and ease of processing, especially in the case of circular economy concepts and regulations like the EU ELV (End-of-Life Vehicle) Directive. To evaluate materials in an integrated way, design engineers often use material selection methods and tools such as Ashby's material selection charts, multi-criteria decision analysis (MCDA), and life cycle assessment (LCA). These tools assist in synchronizing material selection with technical performance, economic feasibility, environmental impact, and manufacturing feasibility. Finally, when it comes to system-level optimization such as part consolidation, joining technique, manufacturability design, and repairability, it is just as vital to the success of composite material integration as material properties.

Table: 3 - Key Criteria for Material Selection in Automotive Components

Selection Criterion	CFRP	GFRP	Natural Fiber Composites (NFC)	Steel	Aluminum
Mechanical Strength	Excellent	Good	Moderate	Excellent	Good
Weight Reduction	Excellent (Very Low Density)	Very Good	Excellent	Poor	Good
Cost	Very High	Moderate	Low	Low	Moderate
Manufacturability	Complex (Needs Autoclave/Prepreg)	Compatible with Compression/RTM	Easy (Low Temp, Low Pressure)	Excellent	Good
Recyclability	Limited (Thermosets)	Moderate	High	Excellent	Excellent
Environmental Impact	High (Energy-intensive processing)	Moderate	Very Low (Biodegradable)	High (CO ₂ emissions)	Moderate
Design Flexibility	Excellent (Tailorable)	Good	Moderate	Poor	Good
Typical Applications	Monocoques, EV structures, high-end parts	Panels, roofs, bumper beams	Dashboards, door panels, trims	Frames, underbodies	Bonnet, suspension arms, crash boxes

6. Challenges and Limitations of Composite Materials in Automotive Applications

Although composite materials possess many advantages, such as improved mechanical performance, design freedom, and lightweighting, the automotive sector still encounters a series of technological, economic, and environmental hurdles before their extensive application. One of the primary detriments is the high cost of production. The material cost of raw carbon fibers, energy-consuming manufacturing processes (such as autoclaving), and complex quality control specifications render advanced composites such as CFRPs expensive. Due to this, they are more viable for performance or high-end vehicles than for high-volume, low-price applications. Another challenge is manufacturing complexity. Scalability and throughput are constrained by processes such as prepreg lay-up, vacuum-assisted resin infusion (VARI), and resin transfer molding (RTM), which require skilled manpower, lengthy cycle times, and precise control. In addition, composite joining techniques are more complex than in metal welding. Mechanical joint and adhesive bonding can require design changes or introduce new stress regions. Composites recycling and end-of-life management, especially of thermosets, are still unresolved issues. A large majority of composites cannot be easily reprocessed without degradation of their mechanical properties, in contrast to metals, which can be melted and reused. Even though thermoplastic composites are more recyclable, their lowered heat resistance continues to restrict their applications in load-carrying functions. The ability to monitor damage and repair composite components is another disadvantage. Composites can suffer from internal delamination or microcracks that are difficult to locate without advanced non-destructive testing (NDT) methods, unlike metals that develop clear deformation. The direction-dependent anisotropic nature of composites requires the application of

sophisticated simulation, test, and optimization techniques during the design process. Finally, variability in the supply chain of natural fibers quite often leads to differences in quality and performance, thus hindering more extensive industrial application.

Table: 4 - Key Challenges and Limitations of Composite Materials

Challenge Category	Description	Impact on Automotive Use	Relative Severity
High Material Cost	Especially CFRP; due to fiber cost and energy-intensive processes	Limits adoption in low-cost vehicles	High
Complex Manufacturing	Precision molding, curing, and handling increase cycle time and costs	Slows down mass production; needs skilled labor	High
Recycling Issues	Thermoset composites are not easily recyclable; thermoplastics limited by temp	Affects sustainability and regulatory compliance	High
Repair and Damage Detection	Internal defects are hard to detect; composite repair is complex	Increases maintenance difficulty and safety risks	Moderate
Joining Difficulties	No welding possible; bonding and fasteners require special design consideration	Reduces ease of integration with other materials	Moderate
Anisotropic Properties	Strength depends on fiber orientation	Requires complex analysis and design optimization	Moderate
Natural Fiber Variability	Inconsistent quality due to agricultural origin	Impacts performance predictability and processing	Moderate
Regulatory Barriers	Lack of standards for composite certification in automotive	Slows down homologation and testing	Low to Moderate

7. CONCLUSION & RESULT

In the automotive industry, composite materials are a game-changer and an efficient way to meet the growing needs for safety, reduced emissions, fuel efficiency, and creative design. This research has shown the strategic use that carbon fiber reinforced polymers (CFRPs), glass fiber reinforced polymers (GFRPs), and natural fiber composites (NFCs) have in lightweighting vehicles and sustaining structural integrity and performance by way of a detailed analysis of different composite types. The complexity and diversity of the process of making composite vehicle parts have been highlighted by the exploration of manufacturing methods. While functional structures have been enabled by processes such as resin transfer molding (RTM), compression molding, and filament winding, these processes often involve compromises on cost, scalability, and processing time. Comparative performance assessment indicated that NFCs offer sustainable alternatives for non-structural uses, CFRPs offer improved strength-to-weight ratios, and GFRPs offer cost-performance compromises. Despite the positive prognosis, several problems still abound, that is, in respect of natural fiber standardization, cost of production, detection of damage, and recyclability. Material

selection strategies, thus, must consider environmental impact, high-throughput manufacturing compatibility, and mechanical as well as economic factors. For achieving full potential for composites in mass-market automotive engineering, these results underscore the importance of integrated design, judicious material selection, and changes in production technique.

Table: 5 - Results

Aspect	Key Observations
Weight Reduction	Composite use can reduce vehicle weight by 20–50% compared to metals.
Fuel Efficiency Impact	A 10% reduction in weight leads to ~6–8% fuel savings (or range extension in EVs).
Performance Comparison	CFRPs: Best strength-to-weight; GFRPs: Balanced; NFCs: Sustainable but lower strength.
Manufacturing Complexity	High for CFRP; moderate for GFRP; low for NFC.
Recyclability	Limited for thermosets; better for thermoplastics and natural fibers.
Cost Implications	CFRP remains cost-prohibitive for mass-market use.
Material Selection Trade-offs	Optimized through performance, cost, design feasibility, and sustainability balance.
Current Applications	Widely used in panels, bumpers, dashboards, seat frames, and EV structural parts.

8. REFERENCE

- [1] A. K. Bledzki and J. Gassan, “Composites reinforced with cellulose-based fibres,” *Prog. Polym. Sci.*, vol. 24, no. 2, pp. 221–274, 1999.
- [2] M. Mallick, *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*, 3rd ed., CRC Press, 2007.
- [3] U.S. Department of Energy, “Lightweight Materials for Cars and Trucks,” EERE, 2020.
- [4] K. Friedrich and U. Breuer, eds., *Automotive Composite Materials*, Springer, 2015.
- [5] G. Marsh, “Composites in automotive,” *Reinforced Plastics*, vol. 54, no. 2, pp. 22–27, 2010.
- [6] A. K. Mohanty, M. Misra, and L. T. Drzal, “Sustainable bio-composites from renewable resources,” *Journal of Polymers and the Environment*, vol. 10, no. 1–2, pp. 19–26, 2002.
- [7] S. M. Sapuan and R. A. Ilyas, “Natural fibre-reinforced polymer composites for automotive applications,” in *Bio-based Composites for High-Performance Materials*, CRC Press, 2020, pp. 153–180.
- [8] D. Gay, *Composite Materials: Design and Applications*, 3rd ed., CRC Press, 2014.
- [9] H. Krüger et al., “HP-RTM: A manufacturing solution for cost-efficient automotive composite parts,” *JEC Composites Magazine*, no. 96, pp. 40–44, 2015.
- [10] M. S. Elfarjani and A. M. Alkhedher, “Cost–benefit analysis of composite materials in automotive applications,” *Materials Today: Proceedings*, vol. 26, pp. 3255–3261, 2020.
- [11] L. Tong, et al., *3D Fibre Reinforced Polymer Composites*, Elsevier, 2002.
- [12] M. J. Ferreira et al., “Recycling of carbon fiber reinforced composites for automotive applications,” *Polymers*, vol. 13, no. 9, pp. 1–22, 2021.
- [13] P. Trivedi and M. Satyanarayana, “Multifunctional composite materials for future electric vehicles,” *Journal of Composite Materials*, vol. 57, no. 4, pp. 673–694, 2023.
- [14] J. Park and Y. Lee, “AI-assisted defect detection in automotive composites,” *Composites Science and Technology*, vol. 217, pp. 109074, 2022.