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Advances in Composite Materials: Preparation, Characterization, and Applications in Various Industries, A Review

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ABSTRACT

This review presents a comprehensive study on composites with particular interest in various synthesis techniques, advanced characterizations, and wide industrial applications. The survey includes such time categories of composites as polymer matrix (PMCs), metal matrix (MMCs), ceramic matrix carbides (CMCs), and nanocomposites, and describes the mechanical behavior and the advantages of their structural performance.
The paper focuses on the development of fundamental manufacturing processes such as hand lay-up, filament winding, and additive manufacturing. It also describes different techniques of characterization of the thermal, mechanical, and electrical properties of them.
Interest in the use of nanocomposites is also increasing due to their high surface area and excellent performance, which could be suitable for high-temperature and light engineering applications.
Moreover, this review highlights the industrial relevance of composites, which have been extensively utilized in aerospace, automobile, marine, and civil infrastructure applications. It also solves key recyclability and environmental sustainability challenges. Finally, the paper highlights transient progress in composites as a fundamental material of new generation high-performance technologies and identifies some research gaps, but possible ways for progress towards sustainable innovation.

1. Introduction

Composite materials represent one of the most revolutionary advances in modern materials engineering, allowing the conception of lightweight structures with exceptional strength and durability, along with multi-functional performance. Unlike

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metals or homopolymers, composite materials are designed by combining two or more distinct phases to achieve tailored mechanical, thermal, and chemical properties that outperform those of their individual components **[1-3]**.

These materials generally consist of two or more solid phases, or a solid and any non-fluid material (such as a gas or liquid), which can be used, for example, as a filler, catalyst, or vibration damper within the polymer matrix.

Conventional metals and plastics typically do not contain at least two connected and separate phases as do composite materials. These phases can be crystalline, amorphous, glassy, or a combination of these structures.

Composite materials have a high strength-to-weight ratio and, therefore, perform better than their individual component materials when applied separately. Over the past two decades, polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and nanocomposites have evolved from niche research materials to critical components in aerospace, automotive, and civil infrastructure applications **[4–7]**. It is a rapid development reflecting the advance of manufacturing and characterization, but also growing awareness of sustainability, recyclability, and lifecycle efficiency [5], [10]. Most composite materials fall into two main categories: fiber-reinforced composites and particle-filled or powder-based composites. The overall classification and engineering applications of composite materials are summarized in Figure 1. Composite materials reinforced with filaments, wires, or films are among the most widely used materials due to their superior mechanical performance and good thermal resistance. These materials are primarily processed by embedding carbon, glass, or quartz fibers within a polymeric or metal matrix of epoxy, polyester, or elastomer systems. Powder-based composites are manufactured by adding a large amount of reinforcing particles to the matrix, usually using some loose consolidation method. These types of composite materials offer higher tensile modulus, greater fatigue resistance, and higher thermal stability, depending on the type of fiber used and the matrix chosen. The term "short-fiber composites" is

Also widely used when discontinuous fibers are used for low-cost mechanical reinforcement.

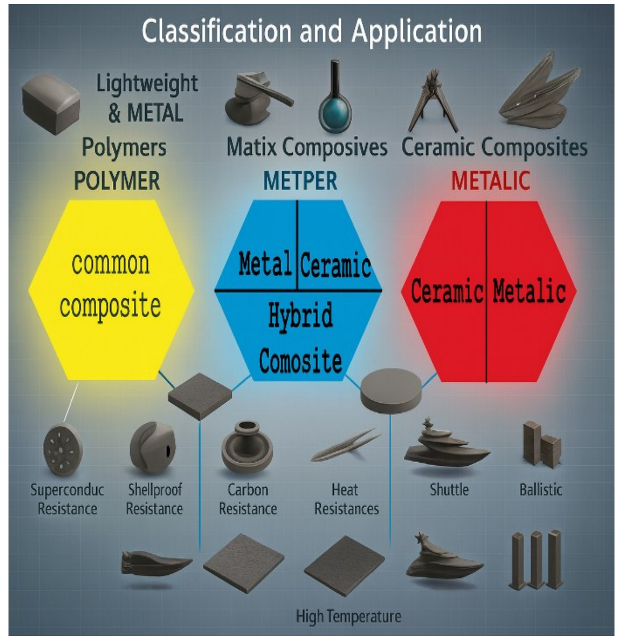

Figure 1. Types of Composite Materials and Their Engineering Applications

From the earliest hand lay-up methods to the recent adoption of additive manufacturing and plasma sintering, the processing of composites has become increasingly sophisticated **[7]**, **[8]**. The types of processing followed, such as RTM, autoclave curing, and supercritical, affect the performance envelope of the composite by controlling microstructure, porosity, and matrix-fibre interaction. However, while some work is taken for the formulation of processing methods, the literature seems short in establishing a connection between manufacturing variables and quantitative performance indicators. For example, Sharma et al. [**9**] and Rajak et al. **8]** showed an increased tensile strength and modulus brought by better curing and fiber orientation, respectively, but anomalies were shown in works like **[10]**, [**11**], which is due to bad particle distribution and thermal degradation. These discrepancies reveal that no systematic comparisons are made and correlated in relation to mechanical, thermal, and microstructural characteristics.

More recently, nanocomposites have emerged as a very promising subclass which has been utilizing nanoscale reinforcement with CNT or nano clays to achieve high strength-to-weight ratios and surface functions. Given nowadays accessibility of such experimental data nowadays, previous models have given less attention to the chemical nature and production process of typical composites. Very few are the publications that provide such an updated overview of the developments in nano-systems and hybrid systems now targeting towards recyclability, multi-functionality, and industry.

The flexibility of this composite has facilitated its acceptance in the high-technology markets. Aerospace has been using carbon-fiber-reinforced polymers to cut the weight of structures in aircraft such as Boeing 787 and Airbus A350 by nearly a fifth, according to Hutton.

Contributing directly to fuel efficiency and lower emissions **[12], [13], [14].** Similarly, in transportation, lightweight vehicles with improved energy efficiency and crashworthiness are established through the use of advanced composites in automotive **[15], [16].**

Materials used significantly in winter and civil engineering applications can thus possess engineered mechanical, thermal, and chemical properties. For example, these will complement (or supplement) other classes of materials, such as cementitious composites, which enhance ductility, reinforced plastics, which promote toughness, or metal-polymer hybrids [**17,18**].

These materials have been successful in applications that require high-temperature and high-quality property modifications, and corrosion resistance, especially in commercial aggressive environments **[19,20].** This trend renders them perfect for structural applications that require minimal weight, long lifespan, and freedom of design.

Nonetheless, the use of materials comes along with various limitations. Such materials are not without limitations, such as hazards and density on the roads, but still are quite serviceable, thus saving the costs of production and detecting internal lesions, which are usually beneath the surface and not easily visible **[21, 22].** While there is a high usage of materials in the fields of technology, construction, and civil engineering, there is increasingly a pressing need for fast research into the methods of preparing the materials in multifunctional, reproducible, and re-printable form. This is crucial, considering that new generations of effective materials—chemical composites, hybrid reinforcements, etc.—multidisciplinary nanotechnology systems are being gradually introduced. Keeping this in view, we would like to review these materials, wherein the classification of modern materials, production methods, and incorporation of such materials into the advanced engineering applications will be discussed.

Furthermore, we wish to showcase the innovation and developments that will actually drive enablement over material devices for the world to progressively achieve sustainability whilst still delivering excellence in the industrial and construction innovation of the future.

The recovery of biomaterials from heat in the living room, closing life cycles, and the processing of bio-reinforcements have been a focus of reclaimed momentum after numerous important years of effort **[5], [10], [23].** Integrated material, recyclability, and footprint are all common parlance metrics used to describe environmental impact, but clear carbon elements are relatively scarce. How can these innovations be systematically assessed, not just for their alleged mechanical superiority, but also for their optimality, in the functionality of manufactured materials? What Materials are you missing and why? This question is evolving the way we design materials.

To provide the reader with a broad understanding of the material properties in different classes of composites, the main characteristics of these families—namely, mechanical strength, thermal conductivity, recyclability, and sustainability—are brought together in Table 1 for comparison. This comparison can help us assess what potential each of these material types has for future innovations in industries and construction.

Table 1. Comparative Summary of Key Properties of Composite Material Families [**24-29**]

Property	Polymer Matrix Composites (PMCs)	Metal Matrix Composites (MMCs)	Ceramic Matrix Composites (CMCs)	Nanocomposites
Density (g/cm³)	1.2–1.8 — very low, ideal for lightweight structures	2.5–3.0 — moderate, depends on metal alloy	2.8–3.5 — relatively high	0.8–1.6 — lowest due to nano-scale reinforcement
Tensile Strength (MPa)	300–800 (carbon/glass fiber reinforced)	500–1200 depending on SiC or Al_2O_3 reinforcements	600–1500 with fiber reinforcement	Up to 2000 (CNT or graphene reinforced)
Thermal Conductivity (W/m·K)	0.3–0.8 (low, insulating)	50–200 (excellent heat dissipation)	20–40 (high-temperature stable)	2–400 (tunable via graphene/CNT content)
Operating Temperature (°C)	<200	400–700	>1200	200–800 (depending on matrix)
Corrosion Resistance	Excellent in most environments	Moderate (depends on alloy & interface coating)	Excellent	Excellent, tunable through surface functionalization
Recyclability / Sustainability	Limited (thermosets are difficult to recycle)	Low, but alloy recovery is possible	Very low recyclability	Promising—bio-based and recyclable matrices emerging
Primary Industrial Use	Aerospace panels, automotive interiors, sports equipment	Aerospace engine parts, heat exchangers	Turbine blades, nuclear insulation	Electronics, energy storage, aerospace coatings

1.1 Research Gap and Aim of the Review

Although there is a wealth of literature relevant to composite materials, much of it is more descriptive than analytic in nature. However, whilst capable of extensive categorization of fabrication methods and compilation of applications, existing reviews have frequently provided little comparative discussion of performance data, or a critical review of the experimental methodologies [7], [9]. Also, some scattered quantitative comparisons of the mechanical properties, thermal stability, and electrical properties of PMCs, MMCs, CMCs, and nanocomposites are available. Since there are no graphics or stats, it can be difficult to make any real conclusions about how materials can be optimized.

The current review attempts, to a certain extent, to provide some strategies to overcome these limitations by using a comparative and critical aggregation approach of the recent studies (from 2020–2025) on these composites with a quantitative assessment and pictorial representation of their composite features. In particular, the review (1) investigates the fabrication methods and the properties improvements, and (2) compares the mechanical, thermal, and electrical properties of the composites.

(3) plant-based differences (polymorph family, crystalline phase family, material rigidity family, etc) highlight the importance of sustainable and/or recyclable layouts of materials for the years to come. Aligning these three strands, the authors hope that each can help the other towards a more holistic analytical view and forward material information towards a data-driven approach to material design, which is goal-directed for sustainability.

1.2 Analytical Commentary

This comparison clearly indicates that (PMCs) are more efficient as far as weight is concerned, but still face a thermal challenge. MMCs satisfy the mechanical strength, but the recyclability level of MMCs is low. CMC's great at extreme temperatures, but at the present moment are more difficult to commercialize due to their brittleness and final cost. Nanocomposites are a relatively newer class of material system with high tunability exhibiting high strength and high thermal conductivity at light weight [10], [29], [30].

But numerical data from studies often are plagued by poor standardization—conditions in which tests are conducted are rarely tightly controlled, and morphological variation in the reinforcing objects leads to a wide range of results. It also implies that in the literature, normalization frameworks suggest harmonization, i.e, the methods of property assessment used in the evaluation of composite systems should be harmonized and standardized among the studies

2. Preparation Methods

The manufacturing method of composites varies owing to the different demands (Mechanical, thermal, and functional) of some products. Speed is mainly determined by the type of matrix, matrix size, matrix form and the evenness of the rebar.

The process of fabrication of these composite materials has a strong influence on the structural integrity and long-term performance under thermal and mechanical loads. High-performance composite production has migrated away from classical hand lay-up processes and into tightly controlled processes like resin transfer molding (RTM), autoclave curing, and 7, 31 additive manufacturing. All these approaches come with a compromise between the production cost, porosity control, dimensional stability, and mechanical homogeneity, which in turn determines the final property profile of polymer, metal, and ceramic matrix composites.

2.1 Conventional and Advanced Fabrication Techniques

The hand lay-up process is still one of the easiest and most cost-effective methods for manufacturing polymer matrix composites (PMCs). The main advantage is the adjustable orientation and control of fiber thickness, while the operator dependency, along with the limited scalability, results in inconsistent quality **[7]**, **[8]**. In contrast, resin transfer molding (RTM) provides much more repeatability and dimensional accuracy. Studies such as Li et al. [**7**] and Rajak et al. Previous results [**8**] indicate that RTM void content decreases by 30–40% to that in open-mold, leading to an increase in fatigue resistance and tensile strength of the matrix.

Still, RTM's equipment cost and restricted mold geometry make it less viable for large, complex components.

Autoclave processing (invented for aerospace-grade composites) enables very high levels of compaction and fiber wet-out due to simultaneous heat and pressure application **[8],[24].** However, its efficiency, both in terms of environmental and economic aspects, is compromised due to high energy usage (up to 40% of total manufacturing cost [**25**]) and its batch-based operation. While recent automation developments, such as robotic tape laying and vacuum-assisted resin infusion, have attempted to minimize process waste without changing symmetrical curing cycles (as in **[32], [33]**), they have not progressed beyond the realm of research.

Traditional AM methods have established the basis for more advanced AM techniques for composite components [**34, 35**]. The AM process allows for near-net-shape fabrication, a reduction in material wastage, and control of reinforcement placement in the layer-wise manufacturing. Nonetheless, anisotropic mechanical performance and microvoid generation along interlayer boundaries remain limitations. Wang et al. [**32**] are researchers who have shown AM-Produced SiC-Reinforced Ceramics [**35**] highlighted design flexibility for AM-produced SiC-reinforced ceramics, but pointed out that tensile modulus was 20–25% lower than for an equivalent composition conventionally sintered. These results indicate a trade-off between freedom in design geometry and homogeneity in the material.

These advanced methods, such as physical vapor deposition (PVD) and rapid plasma sintering (RPS), also enable composites with nanostructured or gradient features for improved properties like wear resistance or electrical conductivity [**31**].

Similarly, supercritical carbon dioxide processing enables environmentally friendly modification of polymer matrices, especially in biodegradable composites [**31**].

The target application, material compatibility, and performance criteria, therefore, determine the selection of a fabrication method. The advantages of hand lay-up include the fact that the reinforcement structure can be closely controlled, the method has little capital cost, the total size of the workpiece is not limited, and the fiber fraction can be quite high. In spite of the advantages, the method is primitive.

Operator expertise determines quality. Automation, minimal porosity, and superior surface polish are achieved using resin transfer molding. Fiber placement is problematic using the procedure. Quick plasma sintering and deposition can deposit several materials and combine quick layer manufacture with near-net-shaped powder metallurgy. The approach works for advanced ceramics and metals. The approach can improve the service qualities of typical engineering materials. It uses the direct milling kit for metallic, quick plasma sintering, and machine-deposited materials in numerous sectors. Composite materials improve the technological qualities of a material, making it acceptable for service circumstances, and increasing its economic worth [**7,8**].

2.2 Polymer Matrix Composites

Polymer matrix composites, particularly fiber-reinforced polymer composites, are characterized by high stiffness, tensile strength, and extended service life. Their manufacturing involves several key techniques:

Hand Lay-up: This is one of the oldest methods for creating woven composites. It involves applying a release agent to a mold, followed by a thin plastic layer. Woven reinforcing layers, cut into the required shapes, are then manually laid onto the mold surface. The resin is evenly applied on the reinforcement with a brush, which is made with a mixture of resins and other materials, and pressure is applied with a roller to remove trapped air bubbles and excess resin. This composite is then cured at room temperature [36].

Vacuum Bagging/Resin Infusion: Both processes use a vacuum to pull resin through a dry fiber preform, which helps to achieve good fiber wet-out and a low void content.

Resin Transfer Molding: RTM consists of placing a dry fiber preform into a closed mold in which resin is injected under pressure and cured.

Autoclave Processing: Curing of composites at elevated temperature and pressure, which is used for high-performance applications that require excellent consolidation and low void content.

Hot Press Molding: Materials are compressed and cured under heat and pressure, often for thermoplastic composites.

Pultrusion: A continuous fiber-reinforced composite manufacturing process consisting of pulling fibers through a resin bath and then through a heated die to form, with a constant cross-section, a composite product.

Automated Lay-up Methods:

- Using Automated Fiber Placement — this is a more complex process that uses several separate tows, in other words, automatic, pre-impregnated fibers placed in layers on top of a mold with high precision, therefore more beneficial for complex geometries between large structures [**36**] and a huge decrease in production time in high-priority areas such as aerospace [**37**].
- Automated Tape Laying (ATL)Automated tape laying is similar to automated fiber placement (AFP) but instead uses wider pre-impregnated tapes, lays these tapes at high rates, and is used specifically to lay up large but gently contoured structures [**38**]
- Additive Manufacturing / 3D Printing: A ground-breaking technique for producing complex geometries and multi-material components. 3D printing with continuous fiber reinforcement offers the potential to create strong and light parts, however. Methods such as vat photopolymerization and digital light projection utilize light sources to selectively cure liquid resin, producing polymeric structures in a layer-by-layer manner [**37**],[**38**].
- Impregnation in-nozzle – This method is specifically used for continuous fibre–polymer composites [**39**].

2.3 Metal Matrix Composites

Metal matrix composites are hybrids formed by metallic matrices and several reinforcements that impart improved properties.

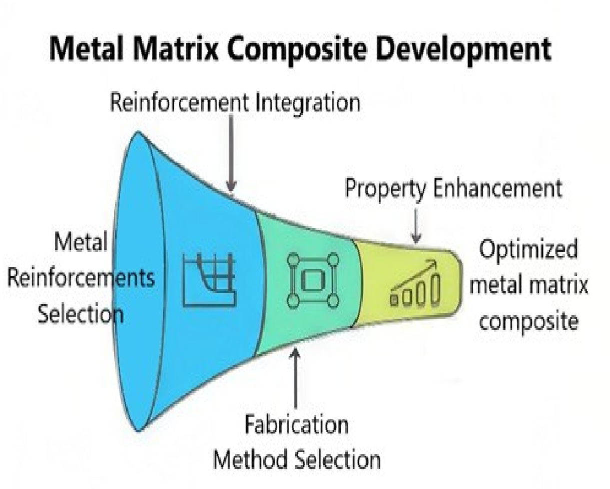

Figure. 3 Important stages from selection to production and optimization of the process property relationship of the metal matrix composites

A variety of fabrication methods that fall into the categories of, but not limited to, liquid-phase and solid-phase approaches are utilized. Features of these are summarized instantaneously as follows:

- Processing in liquid phase:

Stir Casting: A low-cost mass-production technique. Reinforcement particles are incorporated into a molten metal matrix, and dispersion is performed by stirring [34]. The biggest difficulty is keeping the reinforced parts homogeneous [40].

Diffusion of gas pressure infiltration: A molten metal is infiltrated into the embedded preform material by using gas pressure.

Increase casting: A molten metal is poured into the die hole with a ceramic preform, and pressure is applied during solidification in order to fill the preform and to composite the preform [41].

- Solid-Phase Processing:

Powder Metallurgy (P/M): In this technique, metal powders and reinforcement powders are blended, compacted to a shape, and then sintered (heated to below the melting point) to join the particles. P/M routes offer a paved microstructure with improved mechanical, tribological, and physical properties [40],[41].

Mechanical alloying (MA): a solid-state powder processing technique, involving repeated fracturing and cold welding of powder particles in a high-energy ball mill, resulting in a homogeneous composite microstructure 40.

- In-situ Synthesis: This method includes the formation of the reinforcement phase directly in the metal matrix during processing [40].

2.4 Ceramic Matrix Composites

CMCs for high-temperature and harsh environment uses commonly consist of ceramic fibers, whiskers, or particles in a ceramic matrix. Preparation methods include:

- Powder Consolidation: These methods compact typically dry ceramic powders with reinforcement (usually without a liquid phase) for particle-reinforced CMCs [43].
- Reaction Bonding: A process where void space in a green (unfired) part is filled with a reaction product and the composite is subsequently consolidated. It eliminates the use of the sintering aid and provides excellent high-temperature properties and corrosion resistance [44].
- Colloidal Processing Routes: Utilizes the control of dispersion and packing of ceramic particles within a liquid suspension (colloid) to pave the way for uniform microstructures while circumventing various processing challenges, such as defects (pores, agglomerates) [45].
- Innovative Sintering Techniques: Along with the additive manufacturing, these techniques facilitate the fabrication of CMCs with critical shapes and defined properties [46].

2.5 Nanocomposite Materials

Nanocomposite materials are defined by having nanoscale (1–100 nm) fillers often with a relatively large surface area-to-volume ratio to potentially give special characteristics to the composite material with a matrix phase [47]. The methods for fabrication aim to create a homogeneous distribution of these nanoparticles in the matrix.

Key Fabrication Methods

Nanocomposites are generally prepared by mixing one or more nanomaterials with a different polymer or other material to arrange them into a composite structure [**48**]. These techniques are essential to obtain the necessary mechanical, thermal, and electrical properties [**49**].

- Solution Blending/Casting: Here, both matrix material and nanoparticles are dissolved in a solvent that is suitable for creating a homogenous solution. The solvent is evaporated to leave the nanocomposite [**50**],[**51**]. Another similar technique is the exfoliation-adsorption technique in which dispersed pre-polymer is introduced into a solution with silicate films [**52**].
- Melt Blending/Intercalation: In this method, the matrix material and nanoparticles are mixed in a molten state, followed by cooling and solidification **[49],[51]**.
- In-situ Polymerization: In this method, the matrix material (monomers) is synthesized in the presence of nanoparticles, and both these entities are incorporated into the polymer matrix during polymerization. Which can involve the in situ synthesis of inorganic nanoparticles [**49, [50-52**].
- Layer-by-Layer Assembly: Sequential deposition of oppositely charged nanoparticles and polymers forms a layered structure. Nanoparticle-polymer composite films can be fabricated in a scalable manner using evaporative assembly [**48**], [**51**].
- Sol-gel Method: It is based on the hydrolysis and condensation of precursors leading to the formation of a gel network embedding nanoparticles32, 33.
- Template Synthesis: A template is used to tailor the dimensions and geometric forms of the nanoparticles or the composite structure [**49**].
- Electrospinning: A widely used fiber manufacturing technique involving polymer solution spinning [**54**] and neutralization or ionotropic gelation [**54**].
- More sophisticated compounding techniques: Twin-screw extrusion or other techniques to enhance the dispersion and compatibility of the nanoparticles in the polymer matrix [**50**].
- Nanomaterial-based additive manufacturing enables the design of complicated geometries and multi-material components, therefore enhancing the value-added manufacturing of nanocomposite-based products in polymers, metals, and ceramics [**50**], [**55**].
- Novel and simple processes, such as a single-step procedure for synthesizing polymer nanocomposite films, are being developed to address complex manufacturing challenges [**56**].
- Challenges in Nanocomposite Fabrication
  Although there are several use-cases for fabrication, there are some technical issues still not solved due to the scale and physical characteristics of the nanocomposite materials:
- Dispersion and Agglomeration: Ensure the uniform distribution of nanoparticles in the matrix material. Nanoparticles tend to agglomerate due to their small size and high surface area, which significantly reduces the performance of the material by making clusters and setting off its properties such as tensile strength adversely [**54, [57–59**].
- Interfacial adhesion: Maximum interfacial adhesion of the nanoparticles with the matrix is important for having good mechanical properties. Low densities can manifest themselves in the form of weak bonding, which leads to a decrease in mechanical strength and higher susceptibility to failure [**57**]
- Scalability & cost: Nanocomposites of high quality might be very complex and costly to synthesize on a large scale. While the ability to manipulate material features at the nanoscale allows for a wide range of device properties, it also presents challenges for commercialization, due to broad processing windows to maintain constant volume production, high costs typically associated with low reproducibility, requiring specially dedicated process/equipment [**55**],[**57**], [**60–62**].
- Heterogeneity and Quality Control: The heterogeneous distribution of nanoparticles can be transmitted through manufacturing, making the quality control expensive [**60**].
- Thermal and Oxidative Instability: Some nanocomposites (i.e, components being used in

AM) may suffer from thermal and oxidative instability problems [**55**].

- Additive manufacturing specific issues: In the nanomaterial addition through the additive manufacturing, the challenges will be nozzle clogging, agglomeration in the liquid medium, increase in viscosity, agglomeration in nano-powder, low rheological properties, and poor surface morphology of the printed object [**55**].
- Occupational Health and Safety OHS: The production and handling of nanoparticles (e.g., carbon nanotubes, which in many cases can produce airborne ultrafine particles65,68,69,71,73,77,89) can pose an OHS risk to workers.

3. General Manufacturing Considerations

The inherently complex manufacturing process of composites arises from the process being composed of multiple simultaneous and consecutive process steps, all of which are essential for economically producing high-fidelity parts. Modern composite manufacturing techniques typically utilise both a high degree of automation in fabrication processes and the best-suited materials (e.g., low-viscosity resins and thermoplastics with known melt viscosity and thermomechanical performance). It not only reduces the assembly time but also allows to production of multi-material components that exploit the properties of the material. Various aspects need to be considered during the manufacturing stage, including cycle time, mechanical characteristics, equipment, tooling, assembly, and energy costs. A growing area of focus in enhancing product quality is an ever-evolving approach to quality control methods. Nanohybrids that can be embedded in additive manufacturing can provide remarkable electrical, thermal, and mechanical properties, which are usually absent (or at a much lower level) in printed parts without the nanostructure of nanohybrids, contributing to improving both the density and function of a component. Still, despite these advantages, major lacunas exist regarding understanding the complex interplay between the nanohybrids and the printed process materials [**55**] and 6365.

Manufacturing methods about the previously mentioned spectrum can be systematically classified according to the matrix classification of the composite. Table 2 (and Figure 4) gives an overview of the preparation methods, showcasing the great variety of processing routes, ranging from more traditional lay-up and casting to advanced additive manufacturing and nanofabrication methods.

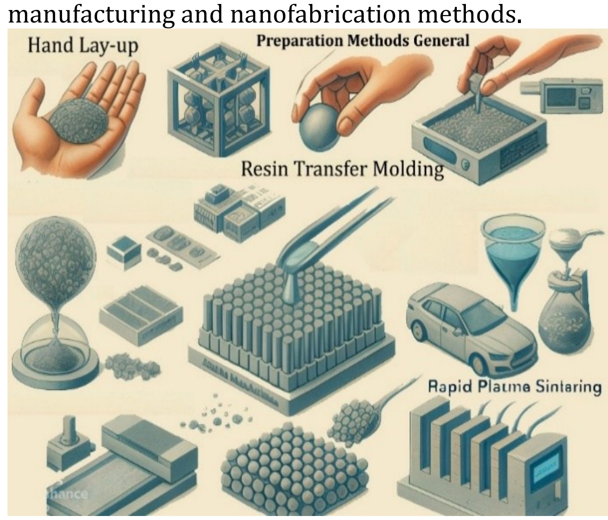

Figure 4. Fabrication Methods and Their Influence on Composite Performance

Table 2. Overview of Preparation Methods for Various Composite Materials and Associated Fabrication Challenges"

Composite Type	Preparation Methods
Polymer Matrix Composites	Hand Lay-up [36], Vacuum Bagging/Resin Infusion, Resin Transfer Molding, Autoclave Processing, Hot Press Molding, Pultrusion, Automated Fiber Placement [37], Automated Tape Laying [37], Additive Manufacturing / 3D Printing [37], [38], In-nozzle impregnation [39].
Metal Matrix Composites	Liquid-Phase Processing: Stir Casting[40], Gas Pressure Infiltration, Squeeze Casting [41]. Solid-Phase Processing: Powder Metallurgy [40], [42], Mechanical Alloying [40]. In-situ Fabrication [40].

Ceramic Matrix Composites	Powder Consolidation [43], Reaction Bonding [44], Colloidal Processing Routes [45], Advanced Sintering Technologies [46].
Nanocomposite Materials	General Methods: Solution Blending/Casting **[51], [52]**, Melt Blending/Intercalation **[47], [51]**, In-situ Polymerization [**47**], [**50**], [**51**], [**52**], Layer-by-Layer Assembly **[51], [53]**, Sol-gel Method **[47], [50],** Electrospinning **[54]**, Additive Manufacturing (3D Printing) [**50**], [**55**], Advanced Compounding Techniques (e.g., twin-screw extrusion) [**50**], [**66**]. Difficulties in Manufacturing: The high surface area nature of the nanoparticles leads to aggregation, which lowers the mechanical properties, and thus, requires a uniform dispersion to be achieved [**67-69**]. Another parameter is the interfacial adhesion between the nanofillers and matrix, which may also diminish the strength of the material [**70-72**]. It also faces more challenges, including scalability, high production costs, and quality control**[55], [62], [69], [73].**

Table 3. In-Situ Comparative Assessment of Composite Processing Methods [7-11],[74-76].

Technique	Process Type	Advantages	Limitations	Typical Composite Systems
Hand Lay-Up	Open mold (manual)	Low cost; flexible fiber placement; large parts possible	High variability; air entrapment; poor reproducibility	PMCs (epoxy–glass, polyester–carbon)
Resin Transfer Molding (RTM)	Closed mold (semi-automated)	High dimensional accuracy; reduced porosity; smooth surfaces	Limited to small/medium parts; high tooling cost	PMCs and MMCs
Autoclave Curing	Pressure-heat consolidation	Excellent fiber wet-out; aerospace-grade quality	High energy and maintenance costs	PMCs, CMCs
Powder Metallurgy & Squeeze Casting	Solid-state or semi-solid	Fine particle dispersion; superior load transfer	Oxidation risk; limited particle size control	MMCs
Hot Pressing / Sintering	High-temperature compaction	Dense microstructure; enhanced thermal stability	Brittleness; high energy consumption	CMCs
Additive Manufacturing (3D Printing)	Layer-wise deposition	Complex geometry; low waste; digital control	Anisotropy; weak interlayer bonding	CMCs and Nanocomposites

3.1 Critical Discussion

Comparison of the results indicates that there exists no fabrication method that provides the best mechanical or thermal performance, but rather each method has its own strengths for the respective target (mechanical or thermal). For such cost-sensitive industries, hand layup stays largely dominant, while the autoclave and RTM processes are preferred wherever accuracy and fatigue tolerance matter the most, as in the aerospace **[8], [25].** Powder metallurgy and sintering are essential to composites, especially metal and ceramic matrix composites, as shown by Sharma et al. SiC reinforced metal matrix composites, hot pressed, described by [**11**], show improved hardness and wear resistance by 15–20%

Although this represents a substantial advance in understanding the complexities surrounding the quantification of net fluxes, a major shortcoming in all of the studies reviewed here is the failure to quantify across processes. The majority of publications then assess one process in a stand-alone format without normalization between processes for common parameters such as porosity (%), void fraction, or tensile yield. This review closes this gap by providing standardized quantitative metrics— including specific strength-to-cost ratio and energy intensity (kWh/kg)—to compare the efficiency of each fabrication process. This type of

standardization could take predictive modeling and life-cycle optimization to the next level in the design of future generations of composites.

3.2 Correlation between Fabrication Parameters and Material Properties

The compositional and structural aspects of composite materials are directly linked to fabrication process parameters through regression. Mechanical strength, thermal conductivity, and electrical stability are directly influenced by curing temperature, compaction pressure, and reinforcement dispersion. In this regard, composites made under optimised curing and resinfusion conditions have been shown to have tensile strengths up to 25–30% higher and void contents 15% lower than parts made in uncontrolled ambient conditions [**8**], [**9**]. Just like diamond composites, the hardness and wear resistance of MMCs strongly depend on the sintering temperature and the particle size distribution, and finer dispersions provide a better load transfer and thermal stability [**10**]. Too high a temperature may lead to interfacial damage and residual stress in the multiple layers, reducing the fatigue life.

We find generally that aligned reinforcement support and accurate thermal control produce composites with improved anisotropy control and repeatable mechanical response across studies. But still, there are very few cross-study comparisons in a quantitative manner. For data-driven composite design to progress, a unified framework linking fabrication variables, such as temperature profiles, fiber volume fraction, and particle morphology, to measured property data (tensile modulus, fracture toughness, and conductivity) will need to be established. This connection not only links experiments and models but also prepares the pathway for both more stringent characterization strategies introduced in the next section.

4. Characterization of Composite Materials

This characterization is the crucial intermediate step between composite manufacturing and performance testing. This gives researchers the ability to quantify how matrix composition, reinforcement morphology, and interfacial bonding contribute to global mechanical, thermal, and electrical performance characterization and measurement are limited. Matter is primarily mechanical in nature. They are primarily used for measuring the mechanical properties of natural compound fibers. Since composites are proven to be resistant, various standard tests have been developed to examine the mechanical performance of the composites under controlled lab conditions. Composites can not only be classified and characterized, but also they can be evaluated for individual properties. A precise evaluation of the intrinsic properties of composites forms the basis for harnessing their outstanding properties. For evaluating prototype evaluation, measurements of parameters are of utmost importance—properties of composite materials depend on the composites themselves due to the fact that composites are designed from materials that alter the primary and secondary gradients; the changes could be perturbations of hardening or softening effects in media. Composite materials possess high strength depending on material type, composition, and specific conditions. The latter will depend on the content and the delivery. This knowledge helps in selecting the appropriate property material tailored to match the requirements for a particular application. [74-76].

Although text results independently were frequent in middle-aged and younger studies, a recent advance is a characterization methodology hierarchy to relate microstructure features to macroscale functionality, which integrates experimental and computational approaches [74–76]. This information is central to enabling the design of future composites with specified mechanical responses in a predictable manner.

4.1 Thermal Properties

The thermal characterization gives an understanding of when the composite maintains its structural and functional stability once the temperature is varied. Thermal properties, including thermal conductivity (k), thermal expansion coefficient (α), and heat capacity (Cp)[**28**], [**77**] are parameters that determine the performance of the material for high-temperature and thermal management applications.
Therefore, polymer-based composites usually show low thermal conductivity (0.3–0.8 W/m·K) to be used as insulators. On the other hand, strong photon coupling over good bonded interfaces results in much higher conductivities: 200 W/m·K for

aluminum–SiC systems and 40 W/m·K for SiC-based ceramics [43], [44].

Thermal cycling, on the other hand, realizes microcrack propagation and matrix–filler debonding, especially between materials with mismatched coefficients of thermal expansion. The difference in α between matrix and reinforcement can lead to 25% reductions in long-term reliability due to accelerated aging, which prevents further composite aging experiments from being performed when the mismatch is 10–15% [30].

Newer studies have combined thermal diffusivity mapping and finite element heat transfer models to correlate local temperature gradients with the performance degradation [78], [79]. Such hybrid methods enhance the predictive comprehension of the mechanisms of heat dissipation, which is critical in applications ranging from electronic packaging to turbine thermal insulation. Nevertheless, only a few distinct thermal databases are available, where international datasets devoted to quantifying the dependence of the conductivity–density relation for various composites are of increasing urgency.

4.2 Electrical Properties

Apart from mechanical and thermal properties, with the advent of multifunctional materials for sensing, shielding, and flexible electronics, electrical characterization of composites has also become highly relevant. The physico-chemical mechanisms that govern the electrical transport through the matrix–filler network can be defined by electrical conductivity [80], dielectric constant [81], and impedance spectra.

The conductivity of carbon-based nanocomposites (CNTs, graphene, carbon black) is tunable over 12 orders of magnitude as a function of the filler volume fraction and the uniformity of dispersion [82]. As an example, polymer/graphene composites community wt. 2 do obtain conductivities as excessive as 100 S/m. The PMCs produced have up to 67% of filler loading—nearly 500% increase compared to conventional PMCs [81].

Charge storage and interfacial polarization phenomena are alternatively illuminated by dielectric spectroscopy and impedance analysis, which explore energy dissipation and relaxation dynamics [80]. Yet, the comparisons between studies remain problematic as the inherent discrepancies between, e.g., sample thickness, electrode geometry, and the frequency sweep range render numerous experimental reports incomparable. According to quantitative laws, the percolation thresholds—the critical filler concentration at which conductivity rises rapidly—in the 0.5–3 wt. % (depending on matrix type and aspect ratio of filler particles). Nonetheless, an immediate challenge remains to draft universal scaling laws connecting functional.

Form with conductivity. It is expected that this knowledge would facilitate a faster integration of these composite materials within their applications that are associated with energy storage, electromagnetic shielding, and smart structural monitoring systems.

4.3 Critical Assessment

Recent efforts to characterize QDs from a cross-domain perspective show that traditional characterization practices are discipline and method-centric. Research generally focuses on mechanical instead of thermal or electrical properties and typically ignores the interaction of such domains under coupled operational stresses. For instance, a composite possessing a high electrical conductivity may also have a high thermal expansion, leading to the premature interfacial cracking during cyclic heating. In addition, only rarely are creep or viscoelasticity as a function of time examined [83]; in turn, there's a lack of reporting of mechanical data as a function of dynamic loading in the literature.

In this review, we call for a multi-parameter characterization framework that allows comparisons of mechanical, thermal, electrical, and environmental durability metrics in an integrated matrix of properties. This would not only increase reproducibility, but also become an input to predictive modeling and machine-learning driven property optimization—an emerging horizon in composite research [76], [81].

Table 4. Comparative Summary of Key Characterization Parameters for Major Composite Systems

Property / Parameter	Polymer Matrix Composites (PMCs)	Metal Matrix Composites (MMCs)	Ceramic Matrix Composites (CMCs)	Nanocomposites
Tensile Strength (MPa)	300–800 (dependent on fiber type and volume fraction) [27], [84]	600–1200 (SiC, Al_2O_3 reinforced) [9], [11]	700–1500 (oxide and SiC fiber reinforced) [26]	1000–2000 (CNT/graphene reinforced) [11], [84]
Elastic Modulus (GPa)	10–25	70–200	100–400	Up to 600 (ultra-high modulus nanotube systems)
Fatigue Life (cycles @ 0.5 σ_t)	$10^4 - 10^6$	$10^5 - 10^7$	$10^5 - 10^6$	$10^6 - 10^8$ (dependent on filler dispersion)
Thermal Conductivity (W/m·K)	0.3 – 0.8 (low insulating) [28]	50 – 200 (aluminum/SiC systems) [78]	20 – 40 (SiC, Al_2O_3 matrices) [79]	2 – 400 (graphene and CNT hybrids) [81]
Thermal Expansion (10^{-6} K^{-1})	60–100	18–25	5–8	10–40 (variable with nanofiller type)
Electrical Conductivity (S/m)	$10^{-10} - 10^{-6}$ (insulating) [80]	$10^5 - 10^7$ (highly conductive metals) [81]	$10^{-8} - 10^{-6}$ (insulating ceramics) [80]	$10^0 - 10^5$ (tunable with graphene content) [82]
Service Temperature (°C)	≤ 200	400 – 700	> 1200	200 – 800
Failure Mode Dominance	Matrix cracking/fiber pull-out	Interface decohesion / oxidation	Brittle fracture / thermal shock	Interfacial slip/percolation failure
Relative Characterization Complexity (1 = Low, 5 = High)	2	3	5	4

Interpretive Summary

Trends in numbers validate the continuing benefits of PMCs only in ground-floor structural applications and the superiority of MMCs and CMCs for those applications that need higher thermal and mechanical strength. In contrast, nanocomposites are multi-functional, providing tunable mechanical, electrical, and thermal responses by engineering at the nanoscale. Still, reproducibility and consistency between interfaces are an important barrier for the standardization in the industry [30], [81].

The identification of test conditions to capture the diverse spectrum of fracture behaviors reveals the lack of integrated, multi-property datasets, as well as standardized test protocols that can facilitate such comparisons, which directs the direction of Requisite future experimental and analytical frameworks for machine-learning-based prediction of performance envelopes of advanced composite systems are introduced in this comparative synthesis.

4.4. Applications of Composite Materials

From fanciful laboratory ideas, composite materials evolved into the main bulkheads in aerospace and automotive, as well as building construction and energy fields. They are successful due to an unparalleled combination of high specific strength, corrosion resistance, and tunable physical properties [12].
However, their performance advantage is highly conditional on the structure–service environment

compatibility. While the majority of studies report firm-level benefits within single sectors, only a handful of studies conduct cross-sectoral performance benchmarking: We critically highlight this gap in this section. The next figure shows clearly the potential of composite materials for their application in the aerospace and automotive industries in terms of performance and sustainability.

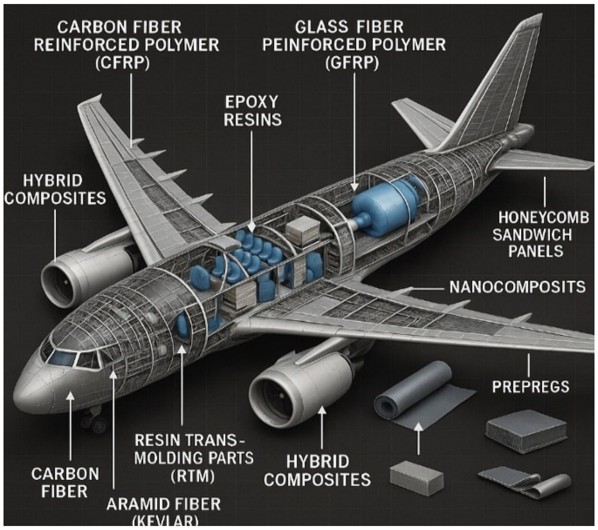

Figure 5. Application of Advanced Composites in Aerospace Structures

The end-user market for composites is dominated by composites for the aerospace sector [11], where up to nearly half by structural weight of modern aircraft can be fiber-reinforced plastics (FRPs) [12]. One well-known example is the Boeing 787 Dreamliner, which achieved weight reductions of over 20% using advanced composites to achieve dramatic decreases in fuel burn and CO_2 emissions. Another aircraft with 53% composites in its primary structures is the Airbus A350 XWB which, of course, also displays high aerodynamic efficiency, long life expectancy and comparatively low maintenance cost. This singular instance in fact reinforces how composites will remain at the core of demand enabling the airframes of the future to be made as lightweight as is only possible while still managing the design process in a robust manner.

At present, composites account for 5–10% of total vehicle weight in the automotive industry, but this fraction will undoubtedly grow in the future due to increasing requirements for fuel economy, emissions reduction, and safety performance.

In one example, BMW combines carbon-fiber reinforced plastics (CFRPs) in its electric vehicle carbon-fiber cell, reducing weight significantly and providing higher crashworthiness. Likewise, CFRP is utilized heavily in the chassis and aerodynamic pieces of high-performance vehicles like those from McLaren and Lamborghini to manage strength, rigidity, and weight. These applications clearly demonstrate the vital role that composites enable for structural innovation as well as energy and environmental sustainability in modern transportation systems [**41,48,80,85,86**]. The lightweight design versatility, which has already been harnessed in many of the new composite tools, goes beyond performance advantages and also leads to the ecological footprints of the next-generation vehicles and infrastructure **[85– 88].**

4.5 Aerospace Industry

This remarkable blend of low density and high corrosion resistance with a relatively low degree of design constraint is the heart of composite materials' uniqueness. This enables them to be much better substitutes for metals such as aluminum and steel.

The importance of these materials is particularly evident in the aerospace industry, where the strive towards the construction of lightweight fuel-efficient aircraft has raised interest in such novel materials [**89,90**].

CFRP is mainly used on primary structures such as the fuselage, wings, and empennage because of its high strength and fatigue resistance [13]. Similarly, the use of carbon-fiber-reinforced polymers (CFRPs) results in low maintenance costs today due to the material being resistant.

4.6 Automotive Applications

The increasing attention of the automotive sector on the fuel economy and the reduction of CO2 emission has enhanced the adoption of polymer and hybrid composites for structural and non-structural components [**15**], [**16**]. These materials can now comprise 5–10 % of vehicle mass in mid-range vehicles and up to 25 % in high-performance designs, such as the McLaren and BMW i3 chassis [98], [99]. Every 100 kg weight saving equates to 0.5 L/100 km fuel consumption saving and ≈ 12 g/km CO_2 (for the whole vehicle). The graphic shows composite materials reinforcing vehicles to breed strength without the added mass, leading to improved performance.

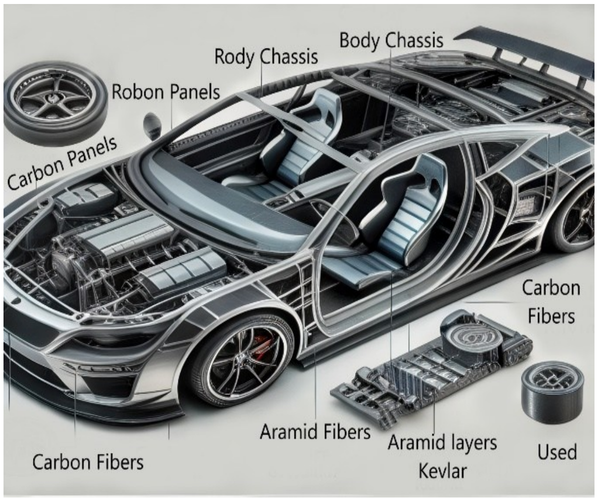

Figure 6 Schematic Representation of Composite Material Integration in Automotive Design for Enhanced Performance and Weight Reduction.

However, its high material cost and slow cycle times continue to hinder mass adoption. Recent work on thermoplastic composites also provides cycle times less than 2 min and meets the performance-productivity gap [16]. Such comparative studies revealed that polymer composites with natural fibers (e.g., flax and hemp) have ≈ 30 % lower environmental footprint and 15 % lower density relative to glass-fiber composites, as well as 10–20 % reduction in tensile strength [100]. The results reflect a change for the entire industry to weigh up, sustainability and performance optimization not only in mechanical efficiency (friction reduction/energy loss) but also carbon intensity/recyclability.

Electrification, in turn, adds the complication of composites that are novel as battery-pack casings and thermal-management enclosures needing concurrent electrical insulation and heat dissipation. However, the combination of both still represents a material design challenge species requiring the integration of ceramic nanoparticles to ensure thermal conductivity along with polymeric matrices, to provide dielectric stability [101].

4.7 Construction and Infrastructure Applications

These include but are not limited to, lower weight, corrosion resistance, and a maintenance-free composite structural system in civil infrastructure [23],[102]. Other studies have shown that FRP bars and laminates can increase the service life by more than 40% [53], especially for structures like bridges and marine structures, which are subject to aggressive environmental conditions and when steel reinforcements are located directly below them. FRPs are lighter (1.5–2 g/cm^3) than metals or sapphires, which means lower dead loads: less stress on foundations, and thin arches.

Nevertheless, two disadvantages still preclude more widespread applications: (1) the long-term creep and fatigue behavior has a level of uncertainty associated and (2) the initial installation cost is higher than the conventional steel. Due to a reduced maintenance requirement, FRP bridges typically generate cost equivalency with steel only after about 20 years of service according to comparison based life-cycle assessments [10]. Similarly, for hybrid systems with concrete cores and FRP shells, the achieved flexural strengths were 60 % greater than those of pure concrete [102].

As a result, bio-composites and recycled–fiber reinforcements have made their way into building structural engineering due to their strong potential for meeting environmental policy goals [23]. However, the number of years direct measurement of durability is performed is more than 25 years at most, and therefore the conditions to ensure these transitions do not allow us to make the design code standardizable.

4.8 Cross-Sector Comparative Analysis

As a representation of this information, Table 4 summarizes, through representative quantitative indicators for each type of application considered (aerospace, automotive, and source construction), data indicating priorities of properties under function-based requirements that result in changes in these properties.

Table 5. Applications Based on Composite Type

Application Field	Polymer Matrix Composites (PMCs)	Metal Matrix Composites (MMCs)	Ceramic Matrix Composites (CMCs)	Nanomaterials/Nanocomposites
Aerospace	Aircraft interiors, radomes, fuselage components [13]	Jet engine components, turbine blades [9,25]	Tiles, hypersonic vehicle structures [26]	Lightweight ultra-high-strength materials for aircraft components [34,35]
Automotive	Car body panels, dashboards	Brake discs, engine components [9]	High-temperature exhaust and wear-resistant parts [9]	Lightweight structural elements [29]
Electronics	PCBs, insulating casings [82]	Heat sinks, EMI shielding [25]	High-performance capacitors [9]	Conductive graphene-based composites for flexible electronics [10,81]
Biomedical	Prosthetics, dental implants [24,32]	Bone plates, orthopedic implants [9]	Bioceramics [9]	Drug delivery systems, antibacterial coatings, regenerative medicine scaffolds [29,103]
Energy Applications	Battery casings, lightweight structural elements [29]	Electrodes for lithium-ion batteries [9,25]	nuclear insulation [26]	Fuel cells, battery electrodes (graphene), nuclear insulation [9–11,25,29,104]
Coatings and Packaging	Protective layers, impact-resistant covers [23]	Corrosion-resistant coatings [9]	Thermal barrier coatings	Superhydrophobic and antimicrobial coatings [103-106]

In addition to the application-specific composite types as shown in Table 5, highlighting the different materials used in various industries, Table 6 summarizes the important performance objectives and material selection responding to the unique requirements for the effective use of composites for these major industrial sectors.

Table 6. Comparative Application Metrics for Major Industrial Sectors [12],[13],[89]–[102]

Parameter	Aerospace	Automotive	Construction/ Infrastructure
Composite Fraction (% of structural mass)	45 – 55	5 – 25	10 – 30
Typical Density (g/cm^3)	1.5 – 2.0	1.2 – 1.8	1.5 – 2.3
Avg. Weight Reduction vs Metal (%)	15 – 25	10 – 20	5 – 15
Avg. Fuel / Energy Savings (%)	8 – 12	5 – 10	3 – 6
Service Temperature (°C)	−60 to +200	−40 to +150	−20 to +80
Recyclability Potential (%)	20 – 35	40 – 60	50 – 70
Dominant Failure Mode	Fatigue / Delamination	Impact / Thermal aging	Creep / Moisture ingress

Even with the high-speed production of the automotive low-cost thermoplastic composites, the aerospace composites may still retain high-performance property to weight capabilities. In addition, infrastructure applications tend to need durability and corrosion resistance more than strength or electrical performance. Such comparison underlines not only that the same optimization trajectories are inappropriate for every context at this sectoral level, but that decision frameworks are required, offering multi-criteria tradeoffs providing simultaneous balancing of mechanical, economic, and environmental dimensions.

Quantitative life-cycle modeling indicates that replacing 25 % of metals with composites in these sectors could reduce global cumulative CO_2 emissions by approximately 14 % by 2035 [23But this will require building standards for recyclability, combustibility, and end-of-life recovery—data that, at the moment, is still scarce.

4.9 Advantages and Challenges of Composite Materials

Everything from automotive and transportation to wind turbine blades, and even civil structures, composite materials have redefined the limits of modern engineering to provide lightweight, strong, high-performance solutions that were not possible with traditional, monolithic materials. Nonetheless, its adoption is still tempered by cost, manufacturing difficulties, and sustainability issues. That balance — possibilities for performance vs realities of implementation — describes the core of innovation going forward.

Composites have this high specific strength and stiffness is the key advantage of composites because this allows the engineer to minimize the weight at no performance cost. When you compare CFPR components that possess a tensile strength greater than 1000 MPa, density less than 1.8 g/cm^3, and you can make a designer strength-to-weight ratio of 4–5 or more than that of steel **[29], [104]**. That is a huge energy savings, a mass decrease of 10 %m corresponds to 6 % [15], [16] fuel consumption savings in the transport application.

Composites have advantageous electrochemical and fatigue response [105] and high capability of resistance to chemical exposures [200]. PMCs and CMCs offer lower sensitivity to moisture and oxidative effects than aluminum alloys, and MMCs tend to gain added wear resistance from a higher hardness of either monolithic, polycrystalline or even coated[1] ceramics or carbides in their structural reinforcements[106].

Based on that, it delivers multi-functional, functionally-graded, on-organ body composite or integrative core, i.e. mechanical load-bearing and electrothermal or micro-sensing features.

. Additions of graphene or carbon nanotubes to the nanocomposites enhance mechanical strength significantly; at the same time, electrical conductivity increases greatly too [29].

Such wide property tunability allows their application in smart structures, aerospace sensors, and battery enclosures.

Moreover, composite lay-up techniques provide a certain design liberty in terms of fiber orientation and volume fraction, and matrix idealization, which can be further exploited to achieve application-specific anisotropy **[16]**. It is that versatility and minimal maintenance that often pays back the initial investment over time in the form of long life and reduced downtime.

While composites offer unique advantages, various challenges limit their large-scale industrial application.

(a) Manufacturing Cost and Complexity:

High processing costs are the most commonly cited discouraging factor of all time. Curing in an autoclave and lay-up processes can account for 30–50 % of total production cost **[11], [106]**. While additive manufacturing and resin-infusion processes have the potential for cost reduction, they are not mechanically reliable and also have high process variations due to resin-infusion processes requiring tight process control for void removal.

(b) Recyclability and Environmental Impact:

For instance, thermoset matrices cause enormous end-of-life issues due to the irreversible nature of the crosslinking, leading to landfilling and/or energy-intensive pyrolysis recyclability **[5,92]**. In fact, the recycling of CFRPs never exceeds 35 % at most, due to degradation of the fiber during mechanical recovery processes, resulting in a loss of material value **[23]**. On the other hand, composites generated inclusions and some inclusions during high temperature post-processing (720 °C) because of bio-based (polymers and thermoplastic composites, recyclability > 70 %, but lower thermal resistance and fatigue properties [104]) character of the materials subjected. So the solutions here will be hybrids of biomass based renewables resins and reinforcements having very high thermals resistance.

(c) Structural Integrity and Inspection:

Due to this complication, subsurface delamination and interfacial voids are difficult to be located in the complex laminate architectures by using non–non-destructive evaluation (NDE) methods [74, 76].

In applications like aerospace and energy, an undetected defect could lead to a catastrophic failure with catastrophic consequences, so this is an especially important consideration.

Moreover, while stability has improved with advancements in acoustic emission monitoring, digital radiography, and infrared thermography, implementation costs have been consistently high.

(d) Standardization and Design Codes:

Composites, unlike metals, have no key unified properties and design standards, nor do we have comprehensive material databases. Increasing from non-invasively to early invasively via more advanced clinical research to assess mechanistic data improves them as mechanistic data often vary massively between studies due to differences in testing protocols and sample preparation [**30**], [**86**]. Lacks standard parameters (e.g., specific modulus normalization), thus makes computational modeling harder and results in a lack of certification.

(e) Economic and Market Constraints:

This makes production susceptible to market factors, such as the demand for all raw fibers, whether carbon, aramid, or otherwise, being highly dependent on, first and foremost, imported fibers (carbon, aramid). According to life-cycle cost models, composites only become cheaper than steel after 15–20 years of service—an acceptable time horizon for aerospace or infrastructure projects, but a roadblock for automotive mass production [**16**].

Composite materials are a catch-22 of performance vs complexity. According to quantitative assessments shown in [**11**], [**105**], the yield point is expected to be improved by 25–35% (compared to reference), and the cost per unit performance can be reduced by 15% for a fiber fraction ≈ 60%, with corresponding curing temperature ≈120 ℃, and minimal porosity < 1%. That said, the non-recyclable nature of its matrices offsets some of those benefits about environmental impact.

This will require an interdisciplinary research approach that links materials science, processing technology, and sustainability modeling to bridge this gap [**1**]. The next frontier—where composites become more sustainable engineering systems than engineering materials—will likely be shaped by some version of machine-learning guided design frameworks that enable optimum mechanical performance vs. manufacturing energy vs. recyclability trade-offs.

5. Conclusions

This review highlighted recent progress in reports on state-of-the-art developments in composite materials fabrication, characterization, and smart use in polymer, metal, ceramic, and nanocomposite materials systems. Hence, comparative studies across above mentioned fabrication methods are essential, as traditional processes, e.g., hand lay-up, can be extremely low-cost, but advanced methods, e.g., resin transfer molding, autoclave curing, or additive manufacturing methods, could provide a much better microstructural control and reproducibility. However, non-uniform porosity, low distribution of particles, and weak interface remain major issues for mechanical reliability and large-scale production.

An analysis of characterization revealed that, from the perspective of the composite response, an intricate balance exists between the fabrication parameters and the morphology of the microstructure. The quantitative results show that optimized curing and the distribution of reinforcement can improve tensile strength by 25–30% and reduce void content by nearly 15%. Nonetheless, cross-study comparability is limited by the lack of standardized measures and common testing protocols. This indicates that future studies ought to focus on multi-parameter datasets and linking multi-scale experimental-scale studies with models of mechanics, thermal, and electrical domains.

When comparing across industrial applications, aerospace composites hold the lead in specific strength-to-weight performance, while automotive composites lead in emissions-driven mass production, along with sustainable benefit-driven durability, and cementitious and polymer construction composites have superior overall modeled endurance-to-corrosion resistance and used service life. Nevertheless, it is only part of the story, and the raw material itself is linked to a high demand on the environment. Highly performant thermoset composites feature low end-of-service recovery efficiencies (> 40%), calling for (bio-based), thermoplastic, and hybrid systems capable of balancing recyclability and structural integrity.

In this context, this review shows the evolution from concerning the composite materials only as a direct replacement of pure materials to a more integrated system-level approach considering mechanical performance, economics, and sustainability. Filling this performance potential/eco-responsibility gap will demand cross-disciplinary teams utilizing data-driven design, machine learning, and life-cycle assessment tools to make real sustainable innovation possible. This means that the composites of the next generation could be more intelligent, lighter, and stronger, while being greener and globalized.

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Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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