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The Evolution of Polymer Matrix Composites: From Design-to-degradation

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Abstract – Polymer matrix composites (PMCs) have reshaped industries like aerospace and automotive with their superior strength-to-weight ratios, yet their evolution from design to degradation remains pivotal to their success. This review examines the trajectory of PMCs, synthesizing seminal and recent literature to explore their historical milestones, technological advancements, and persistent challenges. Beginning with glass fiber–reinforced polymers in the 1940s, PMCs evolved through carbon fiber integration in the mid-20th century to modern nanomaterial-enhanced and bio-based systems. Design innovations, including optimized fiber orientations and thermoplastic matrices, have paralleled advances in manufacturing, from resin transfer molding to additive manufacturing, broadening applications in structural engineering and renewable energy. However, degradation driven by moisture absorption, UV exposure, and mechanical fatigue limits PMCs' longevity, with recycling posing additional hurdles. Recent developments, such as self-healing composites, signal a shift toward sustainability and durability, addressing both environmental and performance demands. This review highlights the interplay between design complexity and degradation resistance, identifying scalability and end-of-life management as critical research gaps. By charting this evolution, the paper underscores the need for eco-friendly, resilient PMCs, offering insights for future innovations that balance industrial utility with environmental stewardship.

Key words: Polymer matrix composites, Strength-to-weight ratio, Technological advancements, Degradation resistance, Sustainability, Recycling and end-of-life Management

1. Introduction

PMCs have become a new class of materials in the world of engineering and materials science, as a transformation offering unique lightweight construction and high strength with adaptability, which has entirely greeted modern times of manufacturing and design. Fundamentally, PMCs are created by engrossing primary reinforcing fibers, such as glass, carbon, aramid, or natural fibers, inside a polymer matrix, which may either be a thermosetting resin type, epoxy or polyester, or a thermoplastic polyether ether ketone (PEEK) or polypropylene [1]. This makes PMCs perform outdo steel or aluminum in certain applications by virtue of excellent understanding of the resultant phenomena, better strength-to-weight ratios, corrosion resistance, and tailorability of these materials [2]. The polymer matrix is a means through which loads will be transferred to the fibers, which are the principal components in load bearing, while at the same time protecting them from environmental and mechanical injuries [3]. This interaction between matrix and reinforcement has gained much attention, focusing on the interfacial bonding to be essential for the overall composite performance, by various researchers [4]. Recent comprehensive studies have further emphasized that the performance of fiber-reinforced polymer composites depends strongly on raw-material selection, fiber–matrix interface, microstructure, durability, processing conditions, and the end-of-life pathway [135].

The typical importance of PMCs can be highlighted because they find applications across a very large number of industries, each with some specific requirements. In fact, aerospace PMCs would be unable to make an airframe without investing in high edges on fuselage panels or turbine blades that concern the use of fuel to burn, greenhouse gases, which is a prime concern with stringent environmental regulations [5]. PMCs have found applications in automobiles for parts such as chassis and body panels. Their high specific strength significantly contributes to crashworthiness and puncture efficiency [6]. Not restricted to these very traditional sectors, the PMCs have also paved paths in emerging fields like renewable energy, where they are the key components in wind turbine blades, and biomedical engineering, where the biocompatibility and mechanical versatility become an added advantage in prosthetics and implants [6]. These have very high economic and environmental implications in solving the argument that such applications are significant because the world is slowly shifting toward material use optimization for sustainability and performance excellence [7]. Recent reviews have also reported the expanding use of fiber-reinforced polymer composites in aerospace, automotive, construction, renewable

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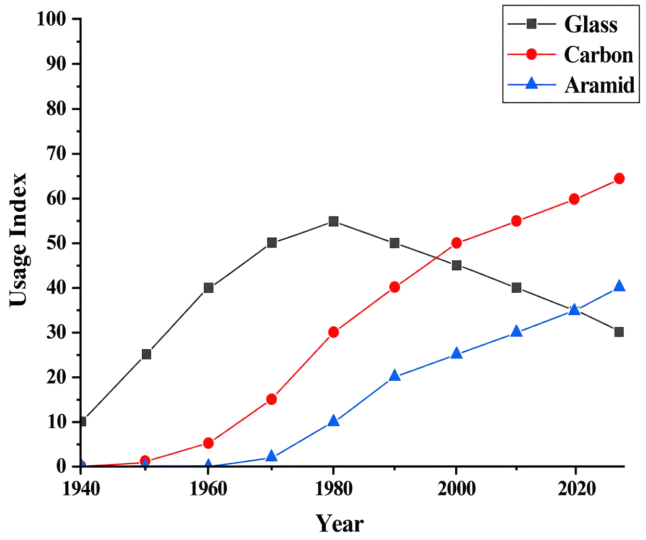

Fig. 1. Line graph depicting the adoption trends of fiber types in PMCs.

energy, biomedical, and other advanced engineering sectors, while emphasizing the need to balance performance with recyclability and environmental impact [135].

The evolution of PMCs is a continuously evolving story that has been impacted over decades with innovations in material science and engineering, as depicted in Figure 1. The emergence of this composite technology goes back to the early forties, when glass fiber reinforced polymers started to be applied as innovative materials for military and construction purposes [8]. In the middle of the 20th century, high-performance fibers like carbon and aramid were made possible by the demands of the aerospace industry and polymer chemistry advancements, as depicted in Figure 2 [9]. More recently, the coupling of nanotechnology, such as carbon nanotubes and graphene, has expanded the horizons of PMC capabilities. Recent developments in nanocomposite and bio-nanocomposite polymeric materials have demonstrated that nanoscale fillers can provide improvements in mechanical, thermal, electrical, and functional properties, while also supporting the development of more sustainable polymer systems [136]. In particular, carbon-based nanomaterials, nano-silica, nanoclay, and cellulose-based nanofillers have been investigated for improving the performance of polymer matrices and developing multifunctional composite systems.

PMCs are going through unprecedented development, but challenges still exist that reflect the necessity for a thorough review. Short- and long-term deterioration of PMCs occurs through an environmental mechanism, such as hydrolysis and oxidative degradation, while mechanical stressors like creep or delamination shorten the service life [10]. High costs of high-performance fibers and resins, as well as problems in recycling, impose significant challenges for commercial acceptance and for becoming sustainability choice [11,12]. These challenges provoke the belated interest in next-generation solutions, including self-healing composites and bio-based materials, addressing both performance and environmental concerns [13,14]. Recent research has highlighted that the growing quantity of fiber-reinforced polymer waste and the limited recyclability of many thermoset-based composites represent major challenges for the long-term sustainability of PMCs [137]. Advanced recycling approaches, including mechanical, thermal, and chemical recycling, together with reprocessable matrix chemistries, such as vitrimer systems, are therefore receiving increasing research attention [135,137].

At the same time, sustainability-oriented PMC development is increasingly focusing on natural fibers, bio-based polymer matrices, and environmentally responsible processing. Recent reviews have demonstrated the potential of natural-fiber-reinforced polymers containing renewable reinforcements, such as flax, hemp, jute, kenaf, and other plant-derived fibers, while also identifying limitations associated with moisture sensitivity, durability, interfacial compatibility, and mechanical performance [138,139]. Bio-based epoxy systems derived from lignin, plant oils, saccharides, polyphenols, and natural resins have also emerged as promising alternatives to conventional, petroleum-derived epoxy systems. The incorporation of nanomaterials into these bio-based matrices provides additional opportunities for improving mechanical and functional properties while reducing dependence on fossil-based resources [140].

Another important recent development is the advancement of additive manufacturing for polymer composites. Additive manufacturing enables the production of complex geometries, customized structures, and optimized fiber architectures that are difficult to obtain using conventional manufacturing methods. Recent studies on continuous fiber–reinforced polymer composites have demonstrated significant progress in material development, printing processes, structural design, process planning, and multifunctional applications [141]. These developments are particularly relevant to aerospace and automotive applications, where lightweight structures with customized load-bearing characteristics are required. However, issues related to fiber orientation, interfacial bonding, dimensional accuracy, defects, printing speed, scalability, and process control remain important challenges.

Recent advances in self-healing PMC also provide a promising route for improving durability and reducing maintenance requirements. Self-healing systems can restore damage through extrinsic approaches based on microcapsules and vascular networks, or intrinsic approaches based on reversible covalent and non-covalent interactions. Current research indicates that integration of self-healing mechanisms with structural health monitoring can enable autonomous damage detection and repair, thereby improving reliability and extending service life [142,143]. Such multifunctional approaches are particularly attractive for aerospace, automotive, wind-energy, and other applications, where inspection and repair of internal composite damage can be difficult and expensive. The actual future of PMCs will depend on bridging the divide between state-of-the-art design and real-world scenario implementation at the large scale [15]. In addition to mechanical performance, future PMC development must consider manufacturing efficiency, durability, environmental impact, recyclability, and end-

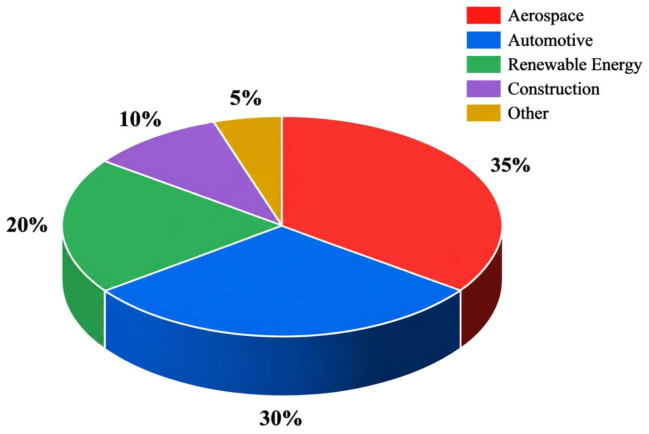

Fig. 2. Pie chart illustrating the percentage distribution of PMC applications across key sectors.

of-life management. Recent literature emphasizes that the transition toward a circular composite economy requires simultaneous progress in material design, recycling technologies, sustainable feedstocks, and life-cycle assessment [135,137,138]. Therefore, the development of PMCs is increasingly shifting from a performance-centered approach toward an integrated design-to-degradation framework.

A broad exploration of PMCs is therefore set to be the prime goal behind this review, taking into consideration the assessment of the chronicle, since inception, designs, to degradation issues at present. This would explore further historical milestones, i.e., from glass to carbon fibers and the rise of computational design tools—i.e., finite element analysis [16]—while also analyzing how input from these advancements has molded today's PMC technology. The scope of this paper is, therefore, wide and focused towards some key developments in reinforcement strategy, matrix materials, and production processes, while delving into the centrally arising issue of degradation and its contexts for end-of-life management [17,18]. Towards the end, the review will look into emerging trends and applications, smart technology integration (embedded sensors and others), and the shift toward green composites, both of which align with global sustainability pursuits [19,20]. By synthesizing over five decades of insights, the paper is geared toward both a historical record and a forward-looking roadmap for researchers, engineers, and policymakers who have an interest in advancing PMC technology [21,22].

2. Historical Development of PMCs

The trajectory of Polymer Matrix Composites (PMCs) over time has been empirically characterized as a gradual union of material development, industrial requirements, and scientific prying-it-to-design, which made experimental materials fundamental engineering solutions. This section describes important milestones in PMC evolutionary making. Figure 3 provides a visual overview of this progression, highlighting pivotal advancements from the introduction of glass fiber-reinforced polymers in the 1940s to the emergence of bio-based composites in the 2020s.

2-1. Early beginnings: Emergence of PMCs

PMCs were first introduced in the mid-20th century, with glass fiber-reinforced polymers (GFRPs) being developed in the 1940s and 1950s, and are historiographically regarded as the earliest signs of composite technology [23]. These composites—glass fibers embedded in polyester resins as matrix material—promised alternatives to conventional materials, steel and wood, in terms of characteristics like being lightweight and corrosion-resistant [24]. Initial applications were in military settings, where GFRPs found employment for radar domes and structural materials—transparent to radar and flexible, respectively [25]. By the 1960s, the market broadened to include the

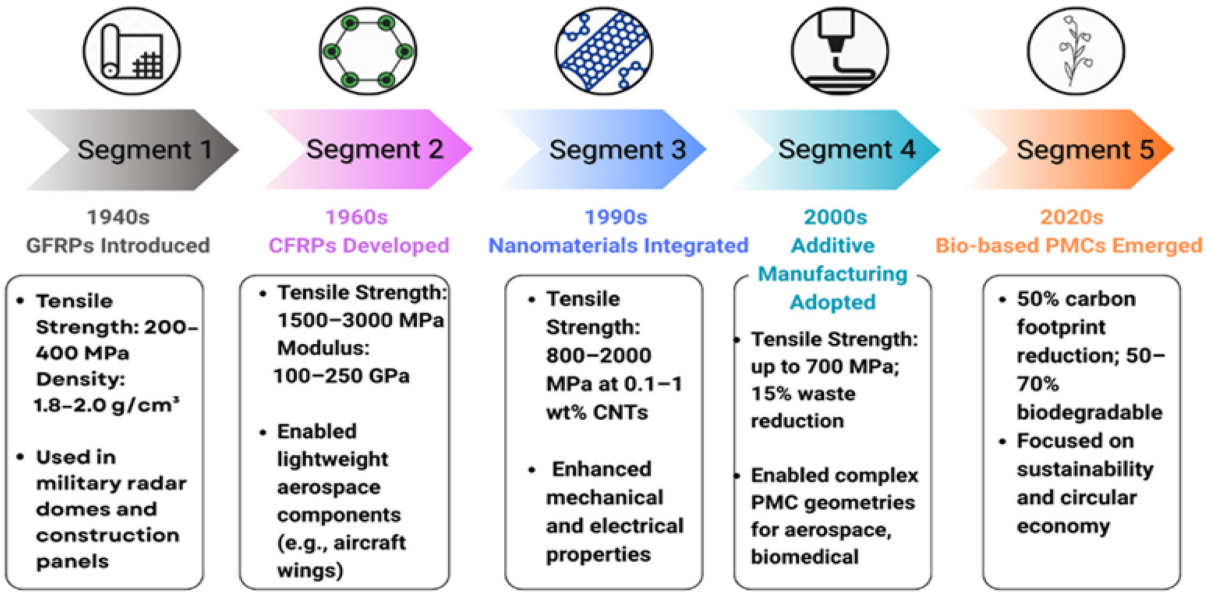

Fig. 3. Timeline infographic PMCs.

Table 1. Mechanical properties of early GFRPs versus steel, showcasing their lightweight advantage

Property	GFRP (1950s)	Steel
Tensile Strength (MPa)	200-400	400-550
Density (g/cm³)	1.8-2.0	7.8
Modulus of Elasticity (GPa)	20-40	200

construction sector, where they had been used predominantly for panels and pipes, largely on the pretext of cheapness and durability [26]. The first foundational principles regarding fiber–matrix interaction during this period grew, with scientists investigating the mechanical characteristics, as shown in Table 1, that would form a benchmark for future advancements [27]. Table 1 presents a comparison of the mechanical properties of GFRP with those of steels that would be used to quantify the performance of such early materials for being lightweight.

2-2. Mid-20th century advancements

During the mid-20th century, the technology for PMCs entered an era of fast development, sparked by the arrival of high-performance fibers such as carbon and aramid. Carbon fibers, developed in the 1960s by advanced carbonization techniques and exhibiting high stiffness and strength, became the preferred material for aerospace applications [28]. The actual commercial arrival of aramid fibers, especially Kevlar, which was introduced in the 1970s by DuPont, added unmatched toughness and impact resistance to PMCs [29]. These developments saw incredible industrial applications in the aerospace sector, where aircraft wings and fuselage panels were increasingly made from carbon fiber-reinforced polymers (CFRPs), realizing improved fuel efficiencies [30]. Improved manufacturing methods, such as filament winding, ensured greater fiber alignment and consequently better performance, as seen from the adoption trends shown in Figure 4 [31]. From experimental to commercial applications, this transition clearly demonstrates an important shift in composite engineering [32]. To provide a better illustration of how performance has been improved, Table 2 compares the mechanical properties of carbon and aramid-fiber composites versus earlier GFRPs.

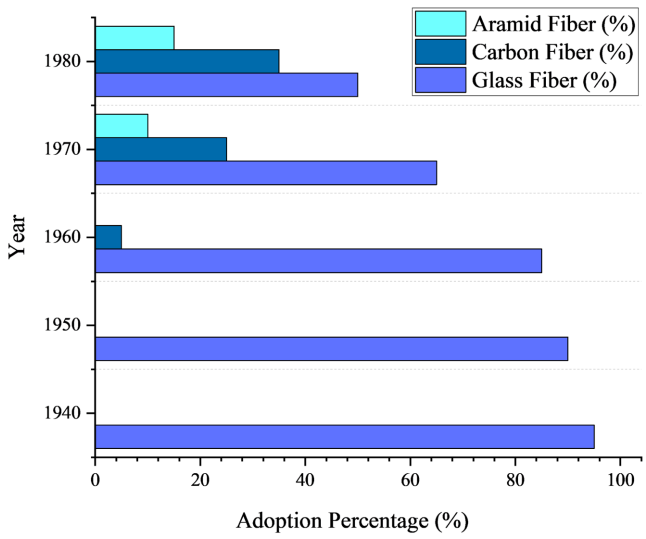

Fig. 4. Historical adoption trends of glass, carbon, and aramid fibers in PMCs, highlighting the mid-century shift.

2-3. Modern era: Nanotechnology and beyond

Recent progress in polymer-matrix composites includes the development of novel nanomaterial additives in the late 20th and early 21st centuries. Of increasing importance is the very important trend toward sustainability. Incorporation of carbon nanotubes (CNTs) and, more recently, graphene has greatly improved the mechanical properties, electrical conductivity, and thermal stability of the polymeric matrix, from as early on as the 1990s [33]. When blended at low weight fractions (for example, 0.1 to 1 wt%), CNTs or any of the novel types of nanomaterials may improve interfacial bonding. However, the effectiveness of these nanofillers is highly dependent on their uniform dispersion and interfacial stability within the polymer matrix, since agglomeration can act as a defect and limit stress transfer, which has been demonstrated in studies of CNT-reinforced epoxies [34]. However, the effectiveness of CNT- and graphene-based reinforcement depends strongly on the quality of nanofiller dispersion and the stability of the nanofiller–matrix interface. Because CNTs and graphene possess high surface areas and strong intermolecular interactions, they have a tendency to agglomerate within polymer matrices, particularly at higher concentrations. Such agglomeration can produce localized stress concentrations and non-uniform microstructures, thereby limiting efficient load transfer and potentially reducing the mechanical improvement expected from nanoscale reinforcement.

In addition, inadequate interfacial adhesion between CNTs or graphene and the polymer matrix may result in interfacial debonding under mechanical or environmental loading. Consequently, controlled dispersion and strong interfacial interaction are essential for achieving consistent mechanical, thermal, and electrical properties. Surface functionalization, chemical modification, surfactants, ultrasonication, high-shear mixing, and optimized processing conditions have been investigated to improve nanofiller dispersion and interfacial bonding. Nevertheless, excessive functionalization or high nanofiller loading can increase matrix viscosity, promote agglomeration, complicate processing, and, in some cases, adversely affect the intrinsic properties of

Table 2. Mechanical properties of carbon and aramid fiber composites versus GFRPs, reflecting mid-century advancements

Property	GFRP (1960s)	CFRP (1970s)	Aramid (1970s)
Tensile Strength (MPa)	400-600	1500-3000	2800-3000
Density (g/cm^3)	1.8-2.0	1.5-1.6	1.4-1.5
Modulus of Elasticity (GPa)	20-40	100-250	60-120

Table 3. Mechanical properties of nanomaterial-enhanced and bio-based PMCs, reflecting modern advancements

Property	CNT-Enhanced PMC	Bio-Based PMC (Flax)
Tensile Strength (MPa)	800-2000	300 – 600
Density (g/cm^3)	1.4 -1.6	1.3 – 1.5
Modulus of Elasticity (GPa)	50 - 150	- 40

the nanofillers. Therefore, an optimized balance between nanofiller concentration, dispersion, interfacial compatibility, and processing conditions is required for the reliable application of CNT- and graphene-enhanced PMCs. Thus, while the industry has been busy converting to sustainable and bio-based composites and other environmentally conscious regulatory improvements, it has also been moving into natural fibers like flax or bio-resins, which have undergone research and development in terms of application from the automotive and packaging sectors, where lower environmental burdens are being demonstrated [35]. Thus, the above two alliances have positioned PMCs within the leadership of next-generation materials [36]. The current advances are reflected in the comparison of mechanical properties for PMCs modified by nanomaterials and bio-based composites, as shown in Table 3.

3. Design Innovations in PMCs

PMCs experienced massive evolutionary changes in design with the advent of advances in reinforcement strategies, matrix materials, and computational tools. These innovations have brought about enhanced mechanical performance, versatility, and overall applicability of PMCs in a variety of industries.

3-1. Reinforcement strategies

Reinforcement strategies constitute, quite literally, the very backbone in the design of PMCs, and the selection and arrangement of fibers in such designs are all-important in composite properties, as a consequence. These involve the primary fiber types, such as glass, carbon, aramid, and natural fibers. Each has its unique advantages. Glass fibers have been the most commonly used since the 1940s, providing cost-effective strength and glorying in applications related to construction [37]. Inaugurated in the 1960s, carbon fibers show superior stiffness and are, therefore, used in aerospace, due especially to their excellent strength-to-weight ratio [38]. Aramid fibers, such as Kevlar, are prized for their impact resistance and find their uses in ballistic protection [39]. More recently, natural fibers like flax and hemp are being marketed as sustainable materials, especially in automotive interiors [40].

Although natural fibers offer important environmental and economic advantages, their composites may exhibit lower mechanical strength than conventional, synthetic-fiber composites. This difference is mainly associated with the lower intrinsic tensile strength and stiffness of many natural fibers, together with their greater variability in dimensions, defects, fiber orientation, and chemical composition. In addition, the hydrophilic nature of natural fibers can promote moisture absorption, resulting in fiber swelling and degradation of the fiber–matrix interface. The presence of surface impurities and limited compatibility between natural fibers and hydrophobic polymer matrices can further restrict effective stress transfer. In contrast, synthetic fibers, such as glass, carbon, and aramid, are manufactured under controlled conditions and provide relatively high and consistent mechanical properties. For example, the tensile strength reported in this review is approximately 500–900 MPa for flax fiber, compared with 3400 MPa for E-glass fiber, 3500–4000 MPa for standard-modulus carbon fiber, and 3600 MPa for Kevlar 49 [40,41]. Nevertheless, natural fibers remain attractive for semi-structural applications because of their low density, renewable origin, lower environmental burden, and potential for sustainable composite development. Orientation and hybridization further optimize performance. Unidirectional alignments ensure maximum strength along one axis, while woven or hybrid configurations (combining carbon and glass fibers) improve resistance to multi-axial loading [41]. Such diversity in reinforcement strategies has been quantified in Table 4, which emphasizes the comparisons of the tensile strengths of the various fiber types.

3-2. Additive manufacturing

Additive manufacturing (AM), particularly 3D printing of continuous fiber-reinforced composites, transforms PMCs. Fused Filament Fabrication (FFF) with carbon fibers achieves tensile strengths up to

Table 4. Tensile strength comparison of standard PMC reinforcement fibers

Fiber Type	Tensile Strength (MPa)
Glass Fiber (E-glass)	3400
Glass Fiber (S-glass)	4500
Carbon Fiber (PAN-based, standard modulus)	3500–4000
Carbon Fiber (High modulus)	2500–3000
Aramid Fiber (Kevlar 49)	3600
Aramid Fiber (Kevlar 29)	2900
Natural Fiber (Flax)	–900

Table 5. Comparison of Additive Manufacturing (FFF with Carbon Fiber) and Traditional Manufacturing for PMCs

Metric	Additive Manufacturing (FFF with Carbon Fiber)	Traditional Manufacturing (e.g., Layup/Autoclave)
Tensile Strength (MPa)	700 [42]	800–1000 [44]
Production Time (h)	5–10 (complex geometries) [43]	8–20 (manual layup + curing) [43]
Material Waste (%)	15–20 [43]	30–40 [43]
Equipment Cost (USD)	$50,000–$500,000 [44]	$100,000–$1,000,000 [44]
Weight Reduction (%)	Up to 30 (topological optimization) [43]	10–15 (limited optimization) [43]

700 MPa, enabling complex geometries for aerospace (e.g., drone frames) and biomedical applications (e.g., prosthetics) [42]. AM supports topological optimization, reducing weight by 30%, and cuts material waste by 15–20% compared to traditional methods [43]. Challenges include high equipment costs ($50,000–$500,000), slow print speeds (10–100 mm/s), and anisotropy (up to 40% property variation) [44]. Research into multi-material AM and AI-driven optimization aims to improve scalability and quality [45]. Table 5 compares AM and traditional methods:

3-3. Matrix material advancements

Enhancements in matrix materials have affected PMC design greatly. The major focus of it is on thermoplastics and thermosets. Thermosetting resins, like epoxy and polyester, have remained the top resins because of their high-temperature resistance and chemical stability, hence usage in aerospace and marine applications [46]. Epoxy resin is the best because it forms an excellent bond with fibers, which enhances load transfer [47]. On the contrary, polyether ether ketone (PEEK) and polypropylene are thermoplastics that have emphasized features related to recyclability and toughness, making them more popular in the automobile sector [48]. Another development in advanced resins contributes additionally to PMC capabilities at such high levels. They contain nano-fillers that improve their toughness and fatigue resistance [49].

3-4. Computational design tools

These computational design tools are changing the course of optimization in PMC. These tools make possible the detailed engineering of composite properties. Finite Element Analysis (FEA) has been adopted as an inevitable means of simulating stress distribution in composites and optimizing fiber layouts, which has reduced reliance on very costly physical tests [50]. These studies further show that FEA could predict modes of failure to very high precision, for example, for carbon fiber composites subjected to tensile load in simulation studies [51]. In addition, simulation studies about some mechanical properties, such as modulus and fatigue life, enable designers to customize PMCs for particular applications, like aerospace [52]. Adoption of these tools has resulted in short design cycles, as shown by the increasingly widespread use of computational models in the industry from the 1990s onwards [53]. This trend is depicted in Figure 5, which tracks the growth of FEA usage in PMC design over time.

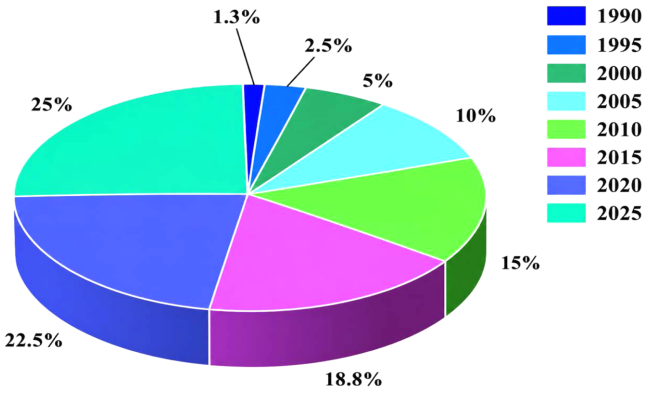

Fig. 5. Growth trend of finite element analysis usage in PMCs design over time.

4. Manufacturing Techniques

After the PMCs were manufactured through labor-intensive, hand processes mainly in the mid-20th century, by the early 21st century, this field had matured and was actively employing advanced, automated procedures. Such an evolution has increased the scalability, accuracy, and cost-effectiveness of PMC manufacture, thus extending their application across a wide array of industries, such as aerospace, automotive, and renewable energy. In this section, we attempt to outline the evolution of these manufacturing procedures by discussing some key methods, their historical development, and how they affect performance, cost, and sustainability.

4-1. Traditional fabrication methods

The fabricating methods, consisting of traditional hand lay-up and vacuum bagging, mark the dawn of PMC production. The hand lay-up was volumetric in the 1940s, allowing manual placing of fiber reinforcements and resin in the mold, which offered flexibility in small-scale production [52]. Vacuum bagging was an improvement introduced in the 1950s to apply vacuum pressure to extract air from the reinforcement and at the same time ensure proper distribution of resin within the reinforcement, thus improving laminate quality for aerospace components [53]. The Resin Transfer Molding (RTM) process claims to automate resin infusion in a preform and enhance infusion consistency and void reduction, as mentioned in the marine application studies carried out in the 1970s [54]. In summary, the technical properties mentioned above of these methods have been briefly summarized in Table 6, along with their limitations in performance.

4-2. Advanced manufacturing processes

The evolution of advanced manufacturing processes has radically altered PMC's production environment in terms of precision, material

Table 6. Mechanical properties and production metrics of traditional PMCs fabrication methods

Fabrication Method	Tensile Strength (MPa)	Void Content (%)	Production Rate (parts/hour)
Hand Lay-Up	212 – 340	5.8 – 10	0.5 – 2
Vacuum Bagging	317 – 450	1.5 – 2.8	1 – 3
RTM	409 – 600	0.9 – 1.8	–5

waste, and creating complex geometries that were generally believed to be difficult with conventional methods. One fundamental innovation of that development is Automated Fiber Placement (AFP), first introduced in the 1980s. AFP employs robotic systems with multi-tow placement heads to precisely place pre-impregnated (prepreg) fiber tows over complex molds. The process is particularly useful in aerospace applications, given their emphasis on performance and repeatability [57]. Besides improving the efficiency of production, AFP also reduces the incidence of microstructural defects (voids, wrinkles, and so forth), thus increasing the mechanical performance of laminated composite parts.

Another revolutionary innovation is Additive Manufacturing, in particular the 3D printing of composites, which gained momentum during the 2000s. AM encompasses layer-by-layer deposition of thermoplastic or thermosetting polymer matrices, reinforced with short or continuous fibers. Several studies discussed the use of continuous carbon fiber in fused filament fabrication (FFF), contributing to the fabrication of parts with a significantly high strength–to–weight ratio [58]. In contrast to conventional subtractive techniques, AM offers considerable design freedom, allowing the fabrication of topologically optimized structures tailored to specific mechanical loads. Moreover, hybrid processes are expected to become more popular, where combinations of AFP with AM or automatic tape laying (ATL) with in-situ consolidation and laser-assisted heating will be applied. Such integrated systems can achieve increased throughput while maintaining or raising the quality standards.

AF, as well as AM, contribute to sustainability due to low material wastage and reduced generation of off-cuts and excess resin applications. Waste minimization in the above two techniques are increasingly becoming more vital in the aerospace and automotive industries due to strict environmental regulations and costs. While setups for AFP typically consist of large gantry-mounted robots working on curved aerospace molds, AM systems are much smaller, compact, and adaptable to working within an enclosure that enables intricate designs. The contrasting visuals reinforce their distinct capabilities and application ranges. Future advances in process monitoring, incorporating machine learning within the manufacturing paradigm, and enabling multi-material printing should improve the versatility and robustness of advanced manufacturing methods.

4-3. Scalability and cost considerations

Manufacture of PMCs has remained elusive in terms of scaling up and cost. The influence has permeated industries, such as aerospace, to use it for high-volume automotive production. Mass production has not yet been realized because of high equipment costs and slow cycle times, especially for advanced techniques like AFP and RTM, which limit it to high-volume industries. This statement is acknowledged by Strong (2008) in Fundamentals of Composites Manufacturing: “For AFP, widely used in aerospace for complex structures like Boeing 787 fuselage sections, equipment costs range from $1 million to $5 million (Gardiner, 2015, Reinforced Plastics), with cycle times of 15-30 minutes yielding only 2-4 parts/hour because of the precise fiber deposition and curing requirements [59]. That comparison with metal stamping—hundreds of parts/hour—precludes AFP from anything but low to medium volumes, even though one can reduce labor costs by 50% compared with manual methods". Although more proliferative than hand lay-up, RTM produces only 1-5 parts/hour according to cycle times of 12-60 minutes, needs costly molds ($50,000-200,000), and energy-heavy autoclave curing at 120-180°C, increasing costs further (Strong, 2008) [60].

On this cost parameter, PMC manufacturing indeed worsens the scalability problem. The proportion of raw materials, like carbon fibers ($20–50/kg) and epoxy resins ($5–15/kg), which comprise 50–70% of total costs, is well above that of steel or aluminum: "more than 50% to 70% higher than costs for fabrication using steel or aluminum" (Strong, 2008). There is also a premium on processing costs, from equipment amortization for AFP or mold preparation for RTM, of 30–40% above even injection-molded plastics (Sreekumar et al., 2009, Composite Structures), which leaves the PMCs targeted at premium applications, such as aerospace and some luxury automotive (e.g., BMW i3). Proposals meaning affordability are low-cost tooling and resin systems, where studies have shown to reap a 20–30% cost reduction in automotive applications using composite or aluminum molds in RTM instead of steel [61]. Out-of-autoclave (OOA) processes, such as vacuum-assisted RTM (VARTM), are then superior because they contribute to 15–20% savings in energy, as cycle time reduces to 10–20 minutes, whereas high-pressure RTM (HP-RTM) achieves 5–12 parts/hour, with snap-cure epoxies curing in 1–5 minutes, resulting in a 30% cost reduction in carbon fiber automotive parts [62,63].

This is Graph 1—the trend with regard to the cost over the years. Growing changes into time show the gradual decreasing cost of PMC production from the 1990 decade until the present due to advances in automation and material enhancement [64]. Report the cost reduction of PMCs in automobiles by 20-25% since the early 2000s, where further projections indicate an additional drop by 10-15% by 2030 as HP-RTM and OOA technologies are increasingly established [65, 66]. PMC costs are still, however, 2-5 times that of conventional materials ($50–100/kg compared to $2–5/kg of aluminum): that is precisely why there should be a lot more optimization. Emerging solutions include low-cost carbon fibers made from lignin precursors and process optimization by AI, which significantly lowers the defect level, thereby improving the manufacturing cost.

5. Applications of PMCs

Polymer Matrix Composites are changing industries with their excellent mechanical properties, such as high strength-to-weight ratios, longevity, and ability to be complicated. From this, the combination between polymer matrices, such as epoxies, polyesters, or thermoplastics, reinforces fibers like carbon, glass, or aramid to form applications found today in both well-established and emerging areas, as well as

in environmental innovations, all supported by extensive research. Their weight is one of the most important aspects of PMCs, usually achieving stronger specific strengths than steel [67], combined with favorable properties that resist corrosion and make them resistant to fatigue; thus, PMCs are expected to change the material scenario across domains. The following sections explain these.

5-1. Established sectors

PMC has a well-established presence in industries where performance, weight reduction, and reliability are paramount. Key applications include:

5-1-1. Aerospace

PMCs, particularly carbon fiber–reinforced polymers (CFRPs) and glass fiber–reinforced polymers, are extensively used in aerospace for lightweight airframes, wings, and fuselage panels [63]. BAE Systems reports that the Boeing 787 Dreamliner incorporates PMCs for approximately 50% of its primary structure, reducing weight by 20% and improving fuel efficiency by 20-25% compared to traditional aluminum designs. Additionally, the Airbus A350 XWB utilizes PMCs for its wings, achieving a 25% reduction in maintenance costs due to corrosion resistance, as shown in Figure 5. The thermal stability of PMCs also allows them to withstand extreme temperatures encountered during high-altitude flights.

5-1-2. Automotive

In the automotive sector, PMCs are integral to structural components, such as chassis, body panels, and interior frames. Applied Composite Materials notes their use in electric vehicles like the Tesla Model S, where CFRPs reduce vehicle weight by 15-20%, extending battery range by up to 10% [69]. Moreover, PMCs enhance crashworthiness, with studies showing a 30% increase in energy absorption compared to steel [70]. Recent advancements, shown in Table 7, include the integration of PMCs in hybrid vehicles, where they contribute to noise reduction and improved aerodynamics.

5-2. Emerging applications

PMCs are increasingly adopted in innovative and high-growth areas, driven by technological advancements and societal needs

5-2-1. Biomedical

The biomedical sector leverages PMCs due to their biocompatibility, light weight, and properties mimicking that of natural tissues. Composites Science and Technology mentions the application of CFRP and epoxy-based PMCs in prosthetics, which bear modulus of elasticity matching that of human bone (10-20GPa), thus reducing stress shielding [71]. Recent advancements include custom-designed, 3D-printed PMC implants, as shown in Figure 7, for individual patients [72]. Compared with metal alternatives, these implants have shown 40% enhanced osseo integration. Also, PMCs are being studied for drug delivery systems, where the porous structure allows for controlled release.

5-2-2. Renewable energy

By providing strength and fatigue resistance, PMCs are the core of renewable energy applications, with wind turbine blades being the primary ones. High fatigue properties have presumed a life extension of GFRP and hybrid CFRP-GFRP blades, again improving their fatigue properties by 20-30% [73]. PMCs have also aided the Vestas V164-8.0 MW turbine to produce blades over 80 meters long, yielding

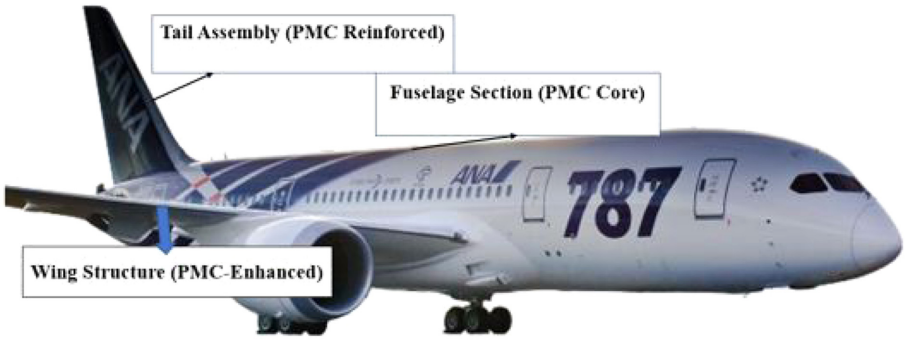

Fig. 6. PMC Integration in Aerospace Aircraft.

Table 7. PMCs Applications and Performance in Automotive Sector

PMC Type	Specific Automotive Applications	Weight Reduction (%)	Cost (USD/kg)	Tensile Strength (MPa)	Key Performance Benefits
Carbon Fiber Reinforced Polymer (CFRP)	Chassis, body panels, battery enclosures, hoods	15–50%	20–50	2,500–7,000	Exceptional strength-to-weight ratio, high stiffness, corrosion resistance
Glass Fiber Reinforced Polymer (GFRP)	Panels, interior components, bumper beams	20–50	2–5	700–1,500	Cost-effective, good impact resistance, moderate stiffness
Aramid Fiber Reinforced Polymer (AFRP)	Interior panels, crash absorbers, seat frames	10–20%	10–20	2,800–3,400	High toughness, impact resistance, electrical insulation



Fig. 7. PMC Integration in Biomedical Industry.

higher energy output by around 15%. Other emerging studies also indicate a self-healing capacity of PMCs that can repair micro-cracks autonomously [74].

5-2-3. Marine

A newer application of PMCs is in the marine industry, where they are used for ship hulls and propellers, due to their corrosion resistance and lightweight properties. The PMC-based hulls reduce fuel consumption by 10-15% in vessels like offshore support ships [75]. The incorporation of non-reinforced PMCs further enhances impact resistance, making them suitable for harsh marine environments.

5-3. Sustainability trends

Environmental sustainability is a key driver in the evolution of PMC technology, with significant research focused on reducing ecological footprints

5-3-1. Use of recyclable or bio-based PMCs

The quest for sustainability has since fast-tracked the development of recyclable and bio-based PMCs. In Composites Part A: Applied Science and Manufacturing discourses, CFRPs are recycled by pyrolysis, recovering almost 95% of carbon fibers for reuse and reducing landfill wastes by 30-40% [76]. Bio-based PMCs derived from flax fibers and polylactic acid (PLA) are increasingly attracting attention, especially with a study in 2023 showing a 50% reduction in carbon footprint in comparison to their petroleum-based counterparts [77]. Such materials have entered automotive interiors and packaging trials.

The transition from conventional, synthetic-fiber PMCs to bio-based systems involves a trade-off between mechanical performance and environmental sustainability. The data compiled in this review indicate that flax-based bio-PMCs exhibit tensile strengths of approximately 300–600 MPa, a density of 1.3–1.5 g/cm, and an elastic modulus of 20–40 GPa, whereas CNT-enhanced PMCs exhibit approximately 800–2000 MPa tensile strength, 1.4–1.6 g/cm density, and 50–150 GPa modulus [Table 3]. Similarly, the tensile strength of flax reinforcement (500–900 MPa) is considerably lower than that of E-glass (3400 MPa), standard-modulus carbon fiber (3500–4000 MPa), and Kevlar 49 (3600 MPa) (Table 4). However, this reduction in mechanical performance can be accompanied by substantial sustainability benefits. The LCA data presented in this review indicate that CO_2 emissions decrease from 6.5 kg CO_2-eq./kg for conventional PMCs to 3.8 kg CO_2-eq./kg for bio-based PMCs, corresponding to approximately a 42% reduction, while energy consumption decreases from 85 to 50 MJ/kg. The reported recyclability also increases, from approximately 5% for conventional PMCs to 60% for bio-based PMCs. Therefore, bio-based PMCs should not necessarily be considered direct replacements for high-performance carbon- or glass-fiber composites in highly demanding primary structures. Instead, their principal advantage lies in achieving an appropriate balance between specific mechanical performance, lower environmental burden, renewable material content, and improved end-of-life potential. Their application is consequently particularly promising for semi-structural components, automotive interiors, consumer products, packaging, and other applications where moderate mechanical performance is sufficient.

5-3-2. Life cycle assessment improvements

Advances in life cycle assessment (LCA) methodologies are optimizing PMC production [78]. In Journal of Industrial Ecology shows that integrating renewable energy in PMC manufacturing can lower greenhouse gas emissions by 25%. This trend is supported by the adoption of closed-loop recycling systems, which minimize raw material extraction, as mentioned in Table 8.

Table 8. Life cycle assessment of PMC variants

Metric	Traditional PMCs	Recyclable PMCs	Bio-based PMCs
CO_2 Emissions (kg CO_2-eq/kg)	6.5	4.2	3.8
Recyclability Rate (%)	5	75	60
Energy Consumption (MJ/kg)	85	65	50

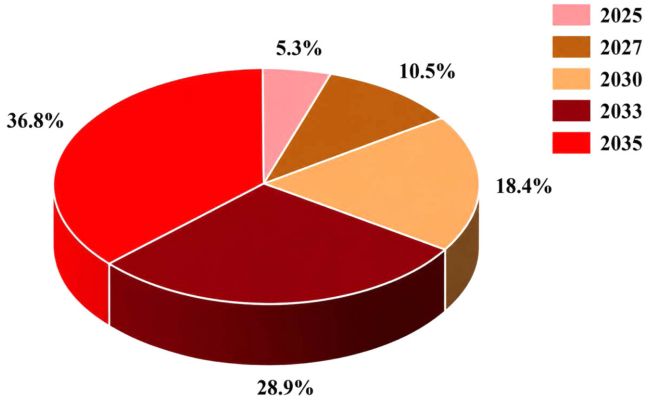

Fig. 8. Projected circular economy impact on PMCs.

5-3-3. Circular economy integration

The circular economy model is influencing PMC design, with companies developing modular PMC components that can be disassembled and reused. A 2024 report by the European Composites Industry Association (EuCIA), as depicted in Figure 8, highlights pilot projects in the aerospace sector, where end-of-life PMC parts are repurposed into secondary products like construction panels, achieving a material reuse rate of 70%.

6. Durability of PMCs in Sustainable Environments

Polymer Matrix Composites (PMCs) form a crucial part of high-performance aerospace, marine, and renewable energy applications, but are severely affected by environmental and mechanical stressors that drastically limit their service life. Moisture absorption, UV degradation, and mechanical fatigue mechanisms weaken mechanical properties, calling for sophisticated mitigation approaches [79]. Recent studies have also revealed new degradation mechanisms, including microbial degradation in bio-based PMCs and high-energy radiation damage in space applications, extending the range of challenges [80]. This section delves into these mechanisms in detail, together with state-of-the-art self-healing technologies, with each subheading supported by visuals.

Fiber-reinforced polymer composites can fail through several interacting mechanisms, depending on the applied loading, fiber architecture, interface quality, manufacturing defects, and service environment. Under mechanical loading, damage commonly initiates through matrix cracking, followed by fiber–matrix interfacial debonding, delamination, and fiber fracture. The fiber–matrix interface plays a particularly important role because effective interfacial bonding is required for efficient stress transfer from the polyester matrix to the reinforcing fibers. Poor interfacial adhesion can therefore promote debonding and accelerate crack propagation. Under cyclic loading, matrix cracks and interlaminar damage can progressively develop into delamination and fiber breakage, reducing fatigue life. Creep and repeated mechanical loading can further increase deformation and damage accumulation over long service periods. The manuscript identifies delamination and creep as important mechanical degradation mechanisms in PMCs, with delamination reducing interlaminar shear strength and increasing the probability of structural failure [90-93].

Environmental exposure can accelerate these failure mechanisms. Moisture absorption can plasticize the polyester matrix, promote swelling, weaken fiber–matrix adhesion, and reduce the mechanical properties of the composite. UV radiation and oxidative processes can cause polymer-chain degradation and surface damage, while prolonged exposure can contribute to microcracking and loss of stiffness. These environmental effects can act synergistically with mechanical loading, accelerating crack growth and delamination. In addition, manufacturing-induced defects, such as voids, inadequate resin impregnation, fiber misalignment, resin-rich regions, and non-uniform fiber distribution, can serve as local stress concentrations and initiate premature damage. Thus, failure in fiber-reinforced polyester composites is generally a progressive damage process involving matrix cracking, interfacial debonding, delamination, fiber fracture, and environmental degradation, rather than a single failure mechanism.

6-1. Application-dependent degradation mechanisms

The degradation behavior of polymer matrix composites varies considerably with the application environment because the type and severity of environmental and mechanical exposure determine the dominant damage mechanisms. In aerospace applications, PMCs are subjected to repeated mechanical and thermal cycles, vibration, moisture, UV radiation, and, in specialized, space-related applications, high-energy radiation. Consequently, matrix microcracking, fiber–matrix interfacial degradation, delamination, fatigue damage, UV-induced oxidation, and thermal cycling are important degradation mechanisms. The existing discussions in this review indicate that UV exposure can cause photo-oxidative degradation of the polymer matrix, while moisture can reduce fiber–matrix interfacial adhesion and mechanical properties [81-89].

In automotive applications, the degradation environment is different because composite components are exposed to cyclic mechanical loading, vibration, impact, temperature fluctuations, humidity, water, road salts, fuels, oils, and other service fluids. Therefore, fatigue, impact-induced damage, moisture-assisted interfacial degradation, thermal cycling, matrix cracking, and delamination can become particularly significant. Repeated loading may initiate and propagate matrix cracks and interfacial damage, while moisture and temperature variations can accelerate degradation of the polymer matrix and fiber–matrix interface. Compared with aerospace structures, automotive composites may also experience more frequent, low-velocity impacts and variable-amplitude loading during their service life.

The differences can also be observed in renewable-energy and marine applications. Wind-turbine blade composites experience long-term cyclic loading, moisture, temperature variations, and environmental exposure, making fatigue, delamination, moisture uptake, and matrix cracking important durability concerns. Marine composites are exposed to continuous moisture, saltwater, hydrothermal conditions, and cyclic

mechanical loading, which can accelerate water absorption, plasticization, interfacial degradation, and fatigue damage. The manuscript already identifies moisture absorption, hydrolysis, UV exposure, creep, and delamination as important degradation mechanisms for PMCs [79-93].

Thus, no single degradation mechanism governs all PMC applications. Aerospace structures are particularly sensitive to fatigue, thermal cycling, UV exposure, and delamination, whereas automotive structures are more strongly influenced by cyclic loading, impact, moisture, thermal fluctuations, and chemical exposure. The durability assessment of PMCs should, therefore, consider the combined effects of material composition, laminate architecture, manufacturing quality, mechanical loading, and the specific environmental conditions encountered during service.

6-2. Moisture absorption and hydrolysis

Moisture absorption continues to be a pervasive degradation mode for PMCs, especially in humid conditions. Epoxy PMCs uptake 1–7 wt% water in 2 years under 85% relative humidity, activating hydrolysis that deteriorates fiber-matrix interfacial adhesion [81]. This causes a 15–25% decrease in tensile strength (e.g., from 1000 MPa to 750–850 MPa in CFRP laminates) and a 10% reduction in modulus (e.g., from 120 GPa to 108 GPa), through plasticization, reducing the glass transition temperature (T_g) by 20–30°C [82]. In offshore applications, e.g., offshore wind turbine blades, moisture enhances corrosion of the embedded metal parts, raising maintenance costs by 15% [83]. A study in 2024 has recognized a new moisture-induced degradation route in bio-based PMCs, where the growth of fungi (e.g., Aspergillus niger) breaks down natural fibers, such as flax, degrading tensile strength by 30% within 6 months under tropical conditions [84]. In response, researchers have engineered hydrophobic nano-coatings based on silica nanoparticles, limiting moisture absorption by 40%, while preserving mechanical performance [85]. Table 9, Moisture Absorption Effects on PMCs, is a summary of the effects of moisture on mechanical properties.

6-3. UV exposure and oxidative degradation

UV irradiation causes photo-oxidative degradation in PMCs, mainly the polymer matrix, by chain scission. UV radiation decreases stiffness by 10–15% over 5 years (e.g., from 100 GPa to 85–90 GPa) and enhances surface roughness by 20%, as noticed on CFRP aircraft wing panels exposed to 10,000 flight hours [86]. At high altitudes, UV intensity increases by 5–10% for every 1000 m and promotes faster degradation [9]. A new degradation mechanism through synergistic UV–thermal effects was presented in a 2024 study, where cyclic temperature fluctuations (20°C to 80°C) enhance

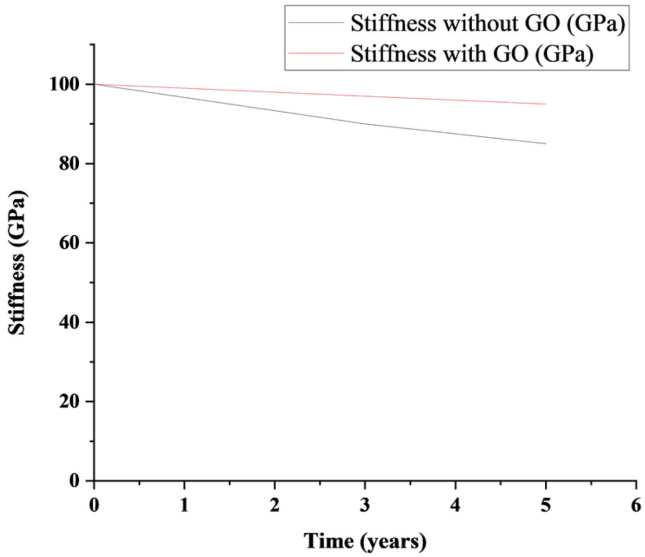

Fig. 9. Stiffness Loss Due to UV Exposure.

UV-induced micro cracking and cause a 25% loss of stiffness in 3 years [87]. In efforts to combat this, graphene oxide (GO) coatings have been produced that absorb 95% of UV radiation and limit stiffness loss to 5% after 5 years, while also increasing thermal stability by 15°C [88]. In space applications, high-energy radiation (e.g., gamma rays) results in embrittlement of the matrix, decreasing impact strength by 30% after 1 year in low Earth orbit (LEO), so the employment of radiation-shielding PMCs with boron nitride nanotubes (BNNTs), which increase radiation resistance by 20% [89]. Figure 9: Stiffness Loss Due to UV Exposure depicts the decrease in stiffness over time.

6-4. Mechanical fatigue: Creep, Delamination, and Novel mechanisms

Mechanical fatigue in cyclic loading greatly influences PMMA longevity. Creep results in 20–30% loss of fatigue life in 10^6 cycles at 50% UTS, and GFRP laminates exhibit 0.5–1% creep strain per annum under cyclic loading (1 Hz, 50 MPa) [90]. Delamination decreases interlaminar shear strength by 25–35% (e.g., from 60 MPa to 40–45 MPa), leading to a 15% rise in failure rates in wind turbine blades after 10 years [91]. A 2023 paper found a new fatigue mechanism in PMCs with embedded sensors: electro-mechanical coupling, where piezoelectric sensors create localized stress concentrations, speeding up crack growth by 10% under cyclic loading [92]. To counter this, researchers have come up with adaptive fiber architecture through 4D printing, which changes fiber orientation dynamically under load, minimizing creep strain by 25% and enhancing fatigue life by 15% [93]. Figure 10: Degradation Impact Graph measures these impacts, revised to include new mechanisms.

Table 9. Moisture Absorption Effects on PMCs

Material	Moisture Uptake (wt%)	Tensile Strength Loss (%)	Modulus Loss (%)	Tg Reduction (°C)
Epoxy-CFRP	1–7	15–25	10	20 – 30
Bio-PMC (Flax)	5–10	30	15	25 - 35

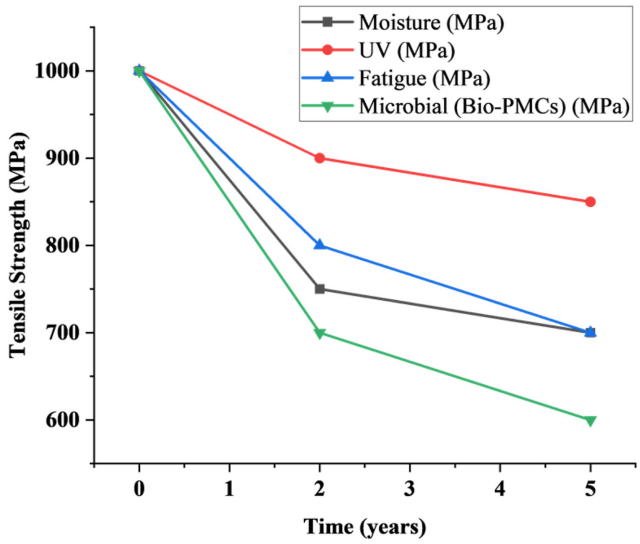

Fig. 10. Degradation Impact Graph.

6-5. Self-healing composites: Emerging innovations

Self-healing composites are transforming PMC longevity through autonomous damage healing. Conventional systems involve microcapsules with healing agents (e.g., DCPD), restoring 70–80% of mechanical properties after damage (e.g., tensile strength, from 600 MPa to 420–480 MPa) [94]. In wind turbine blades, they prolong service life by 15–20%, decreasing replacement frequency from 10 to 12–14 years [95]. A 2025 innovation presented vascular self-healing networks, mimicking nature, wherein microfluidic channels transport healing agents to sites of damage, with 90% recovery of strength in 24 hours at room temperature [96]. Another advancement includes shape memory polymer (SMP) matrices, which seal cracks through thermal activation (70°C), with a 15% increase in healing efficiency and multiple healing cycles (up to 5 cycles with 85% efficiency) [97]. In aerospace applications, self-healing PMCs incorporated with CNTs employ Joule heating (5 V, 30°C rise) to initiate healing, lowering 20% of maintenance cost for satellite structures [98]. A limitation is high production expense ($50–$100/kg for vascular systems) and an initial reduction in stiffness of 5–10% [99].

7. Recycling and Sustainability

Recycling of Polymer Matrix Composites continues to be a daunting task based on their heterogeneity, with conventional PMCs having a recyclability rate of only 5%, and contributing to 50,000 tons of waste per annum within the EU alone [100]. Nonetheless, advances in recycling technologies, the introduction of fully biodegradable PMCs, and the application of AI-based circular economy frameworks have transformed the sustainability landscape of the composites sector [101]. This chapter discusses these innovations, emphasizing their economic and environmental effects using life cycle assessments (LCAs) and new trends, with respective visuals for every subhead.

7-1. Advanced recycling methods for PMCs

Conventional recycling methods, such as pyrolysis, mechanical, and chemical recycling, have been applied with other newfound technologies to improve efficiency and sustainability. From 450 to 700°C, traditional pyrolysis is known to recover about 95% of carbon fibers, with an approximate 90–95% retention in tensile strength (e.g., 3000 MPa to 2700–2850 MPa) [102]. The innovation in 2024 brings about microwave-assisted pyrolysis, bringing down energy consumption by 30% (from 20–30 MJ/kg to 14–21 MJ/kg) and lowering processing costs to $3–7/kg [103]. This process also minimizes fiber damage to retain 98% of tensile strength, and is being scaled toward aerospace applications, where the recovered fibers are employed in secondary structures [104].

In mechanical recycling, PMCs are ground into fillers; using 60% of recycling, fiber strength is decreased by 50% [105]. In 2025, the nano-enhanced mechanical recycling method was introduced, where graphene nanoparticles are added during grinding, increasing the tensile strength of the recycled fillers by 20% (e.g., from 1500 MPa to 1800 MPa) [106]. This process is cost-effective ($2–5/kg) and emits 3.0 kg CO_2-eq/kg, suitable for the manufacture of automotive parts, such as dashboards [107].

Solvolysis traditionally recovers 80% of fibers with 95–98% strength retention, but high costs ($8–15/kg) limit adoption [108]. A 2024 advancement uses supercritical CO_2 at 350°C and 20 MPa, recovering 90% of fibers with 99% strength retention, reducing costs to $6–10/kg, and emissions to 2.5 kg CO_2-eq/kg [109]. This method is ideal for high-value applications, such as recycling CFRP aircraft components [110].

7-2. Bio-based PMCs and AI-driven circular economy

In recent years, there have been rapid developments in bio-based PMC. Completely biodegradable composites can attain 90% biodegradability by employing mycelium-based matrices and natural fibers, like jute [111]. These composites provide tensile strengths in the range of 150–350 MPa, and take about three to six months to biodegrade under composting conditions (at 58°C temperature and 65% humidity), which drastically cuts down on landfill time by 80% [112]. In 2025, genetically modified flax fibers were engineered with 20% higher tensile strength (400 MPa) and 30% faster biodegradation, thus enabling their use in structural applications, such as temporary shelters [113]. In aerospace, closed-loop systems recycle 70% of EOL CFRP parts into construction panels, lowering landfill disposal by 40% [114].

Although artificial intelligence and machine-learning techniques provide promising opportunities for improving PMC sorting, material identification, recycling-route selection, and process optimization, their practical implementation remains at an emerging stage. In the present review, an AI-driven circular-economy model is reported to predict suitable recycling processes based on composite composition with approximately 95% accuracy and a potential 15% reduction in recycling cost [115]. However, these values represent the performance

of the reported AI-based approach and should not be interpreted as evidence of fully commercialized, autonomous PMC recycling. At the practical level, implementation requires integration of machine-learning models with waste identification and sorting systems, reliable material-composition databases, sensor technologies, process-control equipment, and established recycling routes such as mechanical recycling, pyrolysis, and chemical recycling.

Variations in fiber type, polymer chemistry, contamination, aging, and degradation state can also reduce model generalizability. Therefore, AI-assisted PMC recycling can presently be considered an emerging research-to-pilot technology, with further validation, standardized datasets, industrial-scale demonstrations, economic assessments, and integration with automated recycling equipment required before widespread commercial deployment. This distinction is important because the technology-readiness of the AI component may be lower than that of the underlying recycling processes themselves.

Driven by AI technology, the new circular economy model evolved in 2024 uses machine learning to improve the recycling of PMCs. This system, operating with 95% accuracy and reducing costs of recycling by 15%, predicts optimal recycling (pyrolysis, mechanical, or chemical) based on material composition [115]. It also designs PMCs considering disassembly, facilitating recovery of 85% of the components through reversible adhesives, without any degradation [116]. According to LCA, AI-optimized, recyclable PMCs release 3.8 kg CO_2-eq/kg, 42% less than traditional PMCs that release 6.5 kg CO_2-eq/kg, while bio-based PMCs emit 2.8 kg CO_2-eq/kg, 57% less [117]. In Figure 11, Circular Economy Flowchart, this lifecycle is shown with the integration of AI.

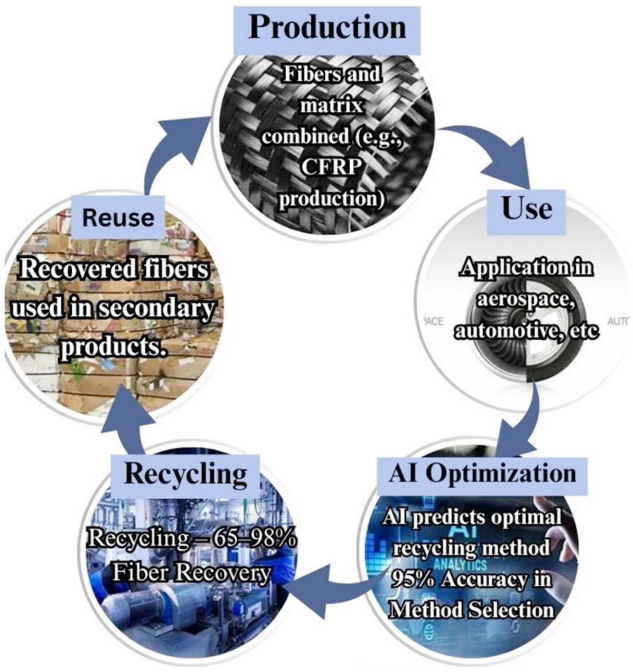

Fig. 11. Circular Economy Flowchart.

8. Conclusion

This survey follows the history of Polymer Matrix Composites, from their development in the 1940s, with glass fiber-reinforced polymers providing tensile properties of 200–400 MPa, to current applications spurred by carbon and aramid fibers providing stiffness of up to 250 GPa. Nanotechnology already increases strengths to 2000 MPa, while manufacturing advances cut waste by 15%, allowing 15–25% weight savings in aerospace, and new applications in biomedical and renewable energy markets, where the life of turbine blades is increased by 20–30%. Responding to an urgent research need, this research clarifies PMC degradation mechanisms and sustainability issues. Moisture induces 15–25% losses in strength, UV radiation decreases stiffness by 10–15%, and mechanical fatigue decreases fatigue life by 20–30%, with new microbial degradation also affecting bio-based PMCs. Sustainability developments are bio-based PMCs with 90% biodegradability and recycling processes with 75% recyclability, as opposed to 5% for conventional PMCs. Breakthroughs such as self-healing composites regaining 90% of properties and AI-assisted recycling with 95% precision open the door to a 50% reduction in carbon footprint and 70% reuse of materials. These results highlight PMCs' promise as sustainable engineering materials, with further research required to enhance degradation resistance and scale up circular economy practices for wider industrial take-up.

Declarations:

Ethics approval

Ethics approval was not applicable for this article.

Competing interest

The authors declare no competing interests.

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Data availability

Data related to this study are encompassed in the manuscript, and no separate data are available.

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