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Review Article

Polymer Composites in Support of the SDGs: Towards Cleaner Mobility, Energy, and Infrastructure

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Abstract - *The Sustainable Development Goals (SDGs) underscore the urgent need for innovative, environmentally responsible technologies to address global challenges in energy, infrastructure, and mobility. The outstanding properties of polymer composites enable them to be used in renewable energy technologies, the provision of clean transportation and in durable infrastructure. In this review, we examine the role of polymer composites in promoting the United Nations SDGs. The principles of the circular economy have been aligned with the recent advancements in materials science research. Improved fuel efficiency and reduced emissions have been supported by the use of polymer composites in the automotive and aerospace industries. The efficiency of wind turbines and solar panels has also been boosted by the use of polymer composites. Even though the use of polymer composites has provided the aforementioned benefits, there remains a challenge with regard to recyclability and standardisation. This review identifies solutions to the emerging limitations of polymer composites, such as the use of green composites. In this review, we highlight the current trends and also future opportunities.*

Keywords - *Polymer, Composites, Energy, Infrastructure, Cleaner mobility.*

1. Introduction

In 2015, the United Nations introduced a set of 17 interrelated targets popularly known as the Sustainable Development Goals (SDGs), which were aimed at tackling global issues [1]. To date, the progress to achieving these goals has not been uniform due to factors such as the Covid-19 pandemic, geopolitical issues and climate change issues [2].

Out of the seventeen goals introduced by the United Nations, SDG 7 on affordable & clean energy, SDG 9 on Industry, Innovation & Infrastructure, as well as SDG 11 on sustainable cities and communities, are important in advancing sustainable development. In order to achieve goals, it is important to come up with solutions that are both efficient and environmentally friendly [3]. Advancements in materials science have the potential to result in efficient energy systems, sustainable infrastructure, and clean transportation solutions [4]. Furthermore, the use of renewable energy sources has advanced recycling and the minimization of carbon emissions [5]. Thus, for the circular economy to be achieved, sustainable materials have to be integrated.

The development of bio-based and recyclable polymer composites aligns with the principle of sustainable development, as they offer environmentally friendly alternatives to conventional materials [7, 8].

The aim of this review is to explore the significance of polymer composites in achieving SDG 7, SDG 9, and SDG 11. The review explores recent trends in polymer composite technologies and their potential to contribute to the SDGs.

2. Overview of Polymer Composites

2.1. Definition and Classification

Polymer composites are made up of a combination of two materials, namely the resin/matrix and the fibres, with the aim of achieving better mechanical properties than the individual constituent materials [9]. Polymer composites can further be grouped into thermosets and thermoplastics. Thermosets cannot be recycled, while thermoplastics can be recycled [10].

Other ways of classifying polymer composites are based on the type of reinforcement. The reinforcement can either be a fibre or a particle. Fibre reinforcement can either be short/discontinuous or long/continuous. Fibrous composites are commonly used in structural applications owing to their high strength-to-weight ratios, while particulate composites are utilized in non-structural contexts where uniform property enhancement is desired [11]. The advancement of nanotechnology has introduced polymer nanocomposites, where nanoclays, carbon nanotubes, or graphene are dispersed within the polymer matrix to achieve exceptional mechanical and functional performance [12].

2.2. Types of Matrix and Reinforcement Materials

The choice of matrix and reinforcement materials significantly influences the final properties of polymer composites. Matrix polymers can be synthetic (e.g. polypropylene) or bio-based (e.g., polylactic acid, polyhydroxyalkanoates), with increasing attention being given to biodegradable matrices for sustainable applications [13]. Among synthetic polymers, epoxies have superior adhesive properties and durability, making them suitable for aerospace and marine industries [14]. On the other hand, bio-based matrices like Polylactic Acid (PLA) offer environmental advantages and are widely used in packaging, medical, and automotive sectors [15].

Reinforcements are typically derived from glass, carbon, aramid, or natural sources such as jute, hemp, and sisal. Carbon fiber reinforcements provide excellent mechanical strength and electrical conductivity but are cost-prohibitive, whereas natural fibers are low-cost, biodegradable, and readily available [16, 17]. Table 1 compares the typical properties of common fiber reinforcements.

Table 1. Comparison of common fiber reinforcements used in polymer composites

Fiber Type	Tensile Strength (MPa)	Density (g/cm³)	Biodegradability	Cost
Carbon Fiber	3,500–6,000	1.75–1.93	No	High
Glass Fiber	2,000–3,500	2.4–2.6	No	Moderate
Aramid Fiber	2,500–3,000	1.44	No	High
Hemp Fiber	550–900	1.48	Yes	Low
Jute Fiber	200–800	1.30	Yes	Very Low

2.3. Key Properties and Advantages

Polymer composites have a high strength-to-weight ratio and superior mechanical properties when compared to metals and ceramics [18]. The high strength-to-weight ratio is particularly useful for applications within the aerospace industry [19]. Polymer composites are also resistant to chemicals, corrosion, and high temperatures, making them useful for extending the service life of components in harsh environments [20]. Polymer composites are also flexible in nature and can be modified to different orientations and distributions [21]. Natural fibre reinforced biopolymers are renewable and have lower carbon footprints [22].

2.4. Recent Advancements and Trends

In recent years, most research has focused on biodegradable matrices and reinforcements. Moreover, there is renewed focus on improving the interfacial adhesion through the use of coupling agents, surface treatments and compatibilizers [23]. Moreover, nanotechnology has made it possible to design nanocomposites through the incorporation of nanofillers such as graphene and carbon nanotubes [24]. There has also been the development of smart composites, where polymer composites are embedded with sensors [25]. Moreover, digital manufacturing techniques such as additive manufacturing, popularly known as 3D printing, have also revolutionized the fabrication of polymer composites [26]. The growing interest in the circular economy has also led to a focus on thermoplastic composites that can be recycled [27, 28].

3. Polymer Composites for Cleaner Mobility

3.1. Application in the Automotive Industry

The high strength-to-weight ratio of composites closely aligns with SDG 13 on climate action. This is because a reduction in the weight of the vehicles will result in lower fuel consumption and reduced greenhouse gas emissions [6, 29].

Automakers such as BMW, Audi, and Toyota have incorporated various grades of CFRPs and Glass Fibre-Reinforced Polymers (GFRPs) in their flagship models to meet regulatory mandates on emissions while enhancing aesthetic and structural features [30, 31]. Table 2 summarizes the comparison between conventional metals and polymer composites in automotive applications.

Table 2. Comparison of properties: Conventional metals vs. Polymer composites in automotive use

Property	Tensile Strength (MPa)	Density (g/cm³)	Biodegradability	Cost
Fiber Type	Steel	Aluminum	CFRP	GFRP
Density (g/cm^3)	7.85	2.70	1.6	2.0
Tensile Strength (MPa)	400–550	200–550	600–2000	300–900
Corrosion Resistance	Low	Moderate	High	High
Fuel Efficiency Impact	Baseline	+10%	+25–30%	+15–20%
Recyclability	High	High	Moderate	Moderate

3.2. Aerospace and Public Transportation

The aerospace sector was among the earliest adopters of polymer composites, leveraging their high strength-to-weight ratios to improve fuel efficiency and reduce maintenance cycles.

The Boeing 787 Dreamliner, for example, is composed of over 50% composites by weight, contributing to a 20% improvement in fuel efficiency compared to conventional aircraft [32].

In the transport sector, the use of composite materials has revolutionized the rail and metro sector, where the high strength-to-weight ratio of the composites has resulted in lower operational and energy requirements [33]. Moreover, the corrosion resistance properties of the FRPs have led to extended service life [34]. The use of flame-retardant composite materials in train interiors has also enhanced passenger safety [35]. Figure 1 shows the impact of composite integration on energy consumption in the transport sector.

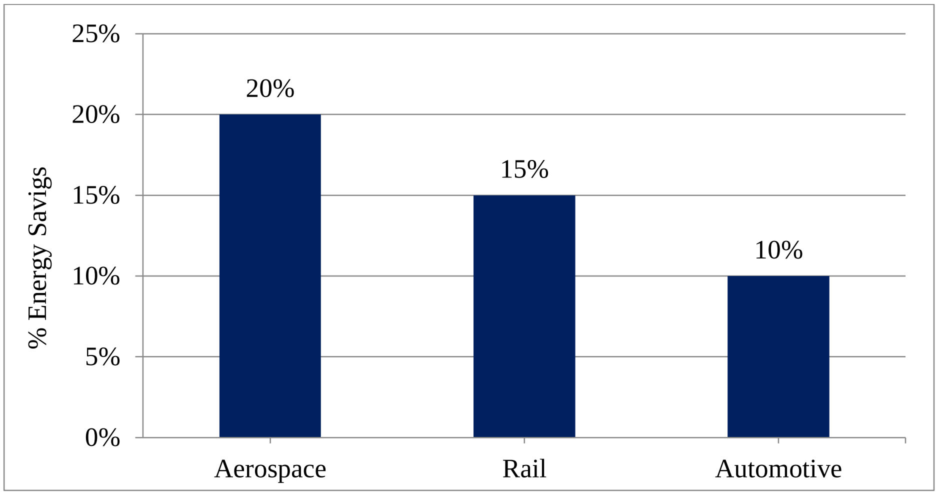

Fig. 1 Impact of polymer composite integration on energy consumption in transport sectors

3.3. Role in Electric Vehicles (EVs) and Hybrids

Electric vehicles need light weighting in order to compensate for the heavy battery packs. As a result of their high impact resistance and flame retardancy, advanced polymers find their applications in battery enclosures, body panels and undercarriage shields [36]. Polymer composites embedded with conductive fillers are used in electromagnetic interference shielding [25]. These materials enhance the operational safety and reliability of vehicles by preventing signal interference in electronic control systems.

Moreover, thermal management is vital for battery longevity and safety. Polymer composites with Phase Change Materials (PCMs) or thermally conductive additives can regulate battery temperatures, reducing the risk of overheating and improving energy efficiency [28]. The multifunctional role of composites in EVs supports SDG 9 and SDG 13.

3.4. Recycling and Circular Economy Approaches

Despite their advantages, the recyclability of polymer composites remains a challenge, especially for thermoset-based systems. However, significant strides have been made toward circularity. Mechanical recycling methods such as grinding and reprocessing are effective for thermoplastics, while chemical recycling-through solvolysis or pyrolysis-can recover fibers and monomers from thermosets [37].

Emerging solutions include the development of reprocessable thermosets based on dynamic covalent bonds, which allow reshaping and reuse without significant property loss [38]. Additionally, bio-based composites, using natural fibers (e.g., flax, jute) and biodegradable resins, offer end-of-life environmental benefits and are gaining traction in mobility applications [39]. Industrial stakeholders are also piloting closed-loop recycling systems. For instance, BMW's i-series includes CFRP components sourced partially from recycled fibers, illustrating the feasibility of sustainable material loops in mass production [40]. These initiatives are essential for aligning polymer composite use with SDG 12.

4. Polymer Composites for Sustainable Energy

4.1. Wind Energy

Polymer composites have played a transformative role in the advancement of wind energy, particularly in the design and manufacture of turbine blades. These blades must be lightweight yet durable enough to withstand variable mechanical loads and harsh environmental conditions.

Modern wind turbine blades can exceed lengths of 80 meters, necessitating materials that offer excellent flexural stiffness and low density. CFRPs, while costlier than GFRPs, offer higher stiffness-to-weight ratios, which are crucial for large offshore wind turbines where load-bearing demands are elevated [41].

Moreover, hybrid composites that combine carbon and glass fibers optimize performance and cost, extending the design capabilities of wind energy systems [42]. Manufacturing technologies such as Vacuum-Assisted Resin Transfer Molding (VARTM) and Automated Fiber Placement (AFP) enable high-quality, large-scale blade production with consistent fiber alignment and minimal void content [43]. Additionally, environmental considerations have led to research into recyclable thermoplastic matrices and bio-based resins, aligning wind energy development with principles of the circular economy [44]. Table 3 shows the comparative mechanical properties of wind blade materials.

Table 3. Comparative mechanical properties of wind blade materials

Material	Density (g/cm^3)	Tensile Strength (MPa)	Fatigue Resistance	Recyclability
GFRP	1.9–2.1	350–900	Moderate	Low
CFRP	1.5–1.8	600–2200	High	Moderate
Hybrid G/C FRP	1.6–2.0	500–1500	High	Moderate
Thermoplastic FRP	1.4–2.2	300–1100	High	High

4.2. Solar Panels and Storage Systems

Composite-based mounting structures made of fiber-reinforced plastics are replacing traditional metal frames due to their reduced weight, corrosion resistance, and ease of installation [45]. These frames are particularly useful for floating solar farms or installations in corrosive environments such as coastal or desert regions. In solar thermal systems and energy storage units, composite materials are used to enhance thermal management. For instance, Phase Change Materials (PCMs) encapsulated in polymer matrices regulate temperature fluctuations and improve storage efficiency [46]. Furthermore, composite housings for lithium-ion and sodium-ion batteries enhance impact resistance, flame retardancy, and thermal insulation, ensuring safety and longevity [47]. Table 4 shows applications of polymer composites in solar energy systems.

Table 4. Applications of polymer composites in solar energy systems

Application Area	Composite Type	Benefits
Encapsulation	EVA, POE + nanofillers	UV resistance, transparency, and durability
Backsheets	PET/GFRP	Electrical insulation, weatherability
Mounting Structures	GFRP, CFRP	Lightweight, corrosion-resistant
Battery Casings	CFRP with flame retardants	Thermal and structural protection
PCM Matrix	Epoxy/PU with paraffin	Thermal energy storage

4.3. Hydrogen and Fuel Cell Technologies

Hydrogen energy systems and fuel cells demand advanced materials that can withstand high pressures, chemical corrosion, and mechanical stress. Polymer composites offer a lightweight and durable solution for storage and transport infrastructure [23-25]. Fuel cell components, such as bipolar plates, benefit from polymer composites reinforced with conductive fillers like graphite or carbon nanotubes. These plates provide electrical conductivity while reducing weight and allowing for easy molding into complex shapes [26, 27].

4.4. Smart and Functional Composites in Energy Harvesting

Smart materials convert mechanical vibrations, thermal gradients, or friction into usable electricity, offering opportunities for powering sensors, wearables, and remote systems [28]. Piezoelectric composites, typically comprising ceramic particles (e.g., PZT) embedded in a polymer matrix, generate voltage under mechanical stress. Their flexibility and adaptability make them suitable for integration into wind blades, bridges, and even shoes for real-time energy capture [29]. Triboelectric Nanogenerators (TENGs) based on polymer composites such as PDMS and PVDF are another avenue, where contact electrification and electrostatic induction produce power from human motion or environmental vibrations [6]. Similarly, thermoelectric composites with embedded nanostructures enhance charge carrier mobility and thermal conductivity balance, improving their energy conversion efficiency [30]. These smart composites are also being integrated into building materials, textiles, and portable electronics, broadening the scope of self-powered devices and reinforcing the push towards sustainable and intelligent energy networks aligned with SDG 11 and SDG 7.

5. Polymer Composites in Sustainable Infrastructure

5.1. Construction Applications

The adoption of thermoplastic composites in modular and prefabricated building systems facilitates rapid construction with reduced waste and lower carbon emissions [31]. This supports urbanization efforts by enabling the development of resilient and energy-efficient housing and infrastructure solutions. Additionally, incorporating natural fibers such as jute, flax, and hemp into bio-composites has emerged as a promising approach for developing eco-friendly construction materials [32]. These bio-composites not only reduce the reliance on synthetic polymers but also enhance biodegradability and reduce environmental footprints. Table 5 summarizes the key advantages of polymer composites over conventional construction materials.

Table 5. Key advantages of polymer composites over conventional construction materials

Property	Steel / Concrete	FRP Composites	Bio-Composites
Corrosion Resistance	Low	High	Medium
Strength-to-Weight Ratio	Moderate	High	Moderate
Ease of Installation	Low	High	High
Environmental Impact	High	Medium	Low
Recyclability	Low	Medium	High

5.2. Corrosion Resistance in Harsh Environments

The long-term performance of polymer composites in corrosive environments has been extensively validated through accelerated aging and exposure tests, which confirm their ability to retain mechanical properties over extended service lives [33]. Additionally, hybrid composites that combine different fiber types and resins are being developed to optimize cost-performance balance and tailor corrosion resistance for specific environments [34].

Figure 2 illustrates the degradation rate of steel versus FRP composites over a 30-year exposure in a marine environment, highlighting the substantial improvement in durability provided by composites.

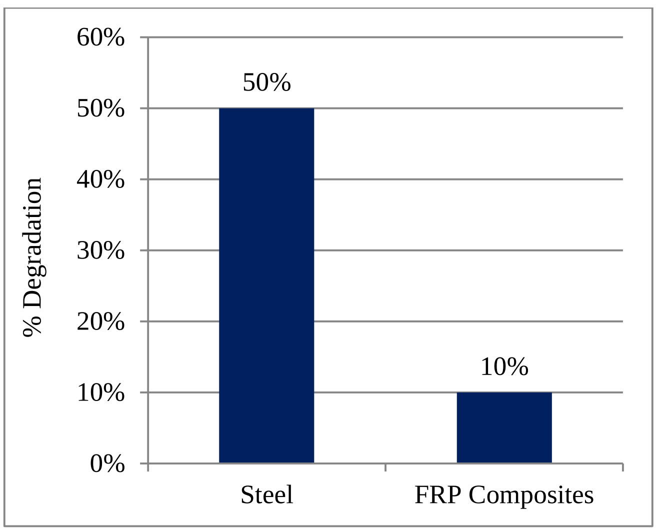

Fig. 2 Degradation rate of steel versus FRP composites over a 30-year exposure in a marine environment

5.3. Use in Smart Cities

As urban centers increasingly transition toward smart city paradigms, polymer composites are being integrated into intelligent infrastructure systems for multifunctional applications. Smart composites, which combine traditional reinforcement properties with embedded sensors and responsive materials, are enabling real-time monitoring of structural health, temperature, humidity, and load conditions [35]. These materials support predictive maintenance strategies and enhance the safety and resilience of urban infrastructure. Moreover, composites play a key role in energy-efficient construction through high-performance thermal insulation materials and Phase Change Materials (PCMs) that regulate building temperatures [36]. Lightweight composite cladding and facade systems also contribute to energy savings by minimizing thermal bridging and enabling passive solar design [25].

In addition, conductive polymer composites are being explored for their potential in wireless communication, electromagnetic shielding, and integration into smart grids, positioning them as a critical component in the future of connected urban environments [28].

5.4. Life-Cycle Assessment and Durability

Life-Cycle Assessment (LCA) is an essential metric for evaluating the sustainability of construction materials, encompassing factors such as raw material extraction, manufacturing, transportation, usage, and end-of-life management.

Polymer composites, particularly those based on renewable or recycled constituents, demonstrate a favorable LCA profile compared to traditional building materials [37]. Studies have shown that FRP-reinforced structures can significantly reduce embodied energy and greenhouse gas emissions over their operational lifespan [38].

Durability is another paramount consideration. Composites exhibit excellent resistance to fatigue, creep, UV degradation, and environmental stress cracking, ensuring long-term reliability in infrastructure applications [39]. Research efforts are also focusing on improving the recyclability and reusability of composite components to align with circular economy principles [40].

Furthermore, the development of self-healing composites-enabled by microencapsulated resins or shape-memory polymers-offers promise in extending service life and reducing maintenance interventions in critical infrastructure systems [41]. Table 6 compares the service life and maintenance frequency of concrete, steel, and polymer composite bridge decks, reinforcing the sustainability advantage of advanced composites.

Table 6. compares the service life and maintenance frequency of concrete, steel, and polymer composite bridge decks

Material	Average Service Life (Years)	Maintenance Frequency (per 10 Years)	Notes on Sustainability Benefit
Concrete	40–50	3–4	Prone to cracking and chloride-induced corrosion
Steel	30–40	4–5	Requires regular anti-corrosion treatment
Polymer Composites	75–100	1–2	Highly resistant to corrosion, low life-cycle cost

6. Environmental and Economic Impact

6.1. Contribution to Carbon Emission Reduction

Polymer composites significantly contribute to reducing carbon emissions across various industrial sectors due to their lightweight nature and high durability. In transportation, for instance, reducing the weight of vehicles by integrating polymer composites can lower fuel consumption and related CO_2 emissions by up to 30% [42]. This aligns closely with SDG 13 (Climate Action) by addressing emissions from road transport, aviation, and marine sectors, which are major contributors to global greenhouse gas emissions.

Moreover, polymer composites are often used in renewable energy technologies, such as wind turbine blades and photovoltaic panels, which play critical roles in decarbonizing the energy sector [43]. The lower embodied carbon in composite manufacturing, especially when using recycled or bio-based materials, also contributes to a favorable emissions profile compared to traditional materials like steel or aluminum [44]. Life-cycle carbon footprint assessments consistently demonstrate that FRP and bio-composites offer 20–50% lower CO_2 emissions than conventional alternatives in construction and infrastructure applications [45].

6.2. Energy Savings over Life-cycle

Polymer composites provide substantial energy savings over the product life-cycle by reducing energy consumption in the usage phase due to their excellent thermal insulation and lightweight characteristics. In buildings, composite panels and insulation systems lower heating and cooling loads, thereby enhancing energy efficiency and reducing operational costs [46]. In transportation, energy use decreases directly due to reduced mass, which improves fuel economy or extends battery life in electric vehicles [47].

Additionally, during the manufacturing phase, thermoplastic composites often require less energy compared to metals or thermosetting materials, particularly when employing automated processes such as resin transfer molding and additive manufacturing [11]. Composite rotor blades in wind turbines exemplify life-cycle energy savings, with studies showing Energy Payback Times (EPBTs) of less than one year for a typical 2.5 MW turbine [12]. Table 7 illustrates the comparative life-cycle energy consumption between steel, aluminum, and polymer composite structures across several sectors, demonstrating the efficiency gains offered by advanced composites.

Table 7. Comparative life-cycle energy consumption of structural materials across sectors

Sector	Material	Life-Cycle Energy Consumption (MJ/kg)	Relative Efficiency Comment
Transport	Steel	35–50	High mass increases fuel consumption
	Aluminum	150–200	Lightweight, but high production energy
	Polymer Composites	90–110	Balance of low weight and lower in-use energy
Construction	Steel	40–60	Corrosion protection adds to life-cycle energy use
	Aluminum	180–210	Rarely used due to cost and embodied energy
	Polymer Composites	95–120	Superior thermal insulation and corrosion resistance
Marine	Steel	50–70	High maintenance and repainting energy
	Aluminum	160–190	Lightweight but susceptible to galvanic corrosion
	Polymer Composites	85–105	corrosion resistant

6.3. End-of-Life Management: Recycling and Biodegradability

End-of-Life (EoL) management of polymer composites remains a critical concern but is evolving with emerging recycling and biodegradation technologies. Mechanical recycling, chemical depolymerization, and pyrolysis are being developed to recover fibers and resins from composite waste [13]. Although thermoset composites are traditionally difficult to recycle, advances in reversible cross-linking polymers and vitrimeric matrices show promising recyclability pathways [14]. Biodegradable composites incorporating natural fibers and bio-based matrices such as Polylactic Acid (PLA), Polyhydroxyalkanoates (PHAs), and Thermoplastic Starch (TPS) offer end-of-life advantages through composting or degradation in environmental conditions [15]. These materials are increasingly used in packaging, construction, and consumer goods to meet the growing demand for eco-design and circularity [16].

Comparative LCA studies have shown that bio-composites outperform conventional composites and polymers in end-of-life scenarios due to their reduced toxicity and environmental burden [17]. The integration of digital tracking technologies, such as blockchain or RFID, also facilitates better EoL traceability and promotes recycling incentives in industries adopting Industry 4.0 principles [18].

Table 8 compares the recyclability and biodegradability of different polymer composites based on their matrix and reinforcement types.

6.4. Economic Feasibility and Market Trends

Economically, polymer composites are becoming increasingly feasible as material costs decline and processing technologies advance. Although the initial cost of composites is generally higher than traditional materials, the long-term benefits-including reduced maintenance, improved durability, and energy efficiency-often result in lower Total Cost of Ownership (TCO) [19].

In infrastructure, for example, FRP bridge decks have demonstrated life-cycle savings of up to 35% compared to steel-reinforced concrete, despite higher upfront costs [20].

The global composites market has shown robust growth, driven by demand in automotive, aerospace, construction, and renewable energy sectors. According to market analysis, the global polymer composites market is projected to reach USD 180 billion by 2030, with a Compound Annual Growth Rate (CAGR) of over 7% [21]. Asia-Pacific and North America lead in composite production, while Europe is advancing in sustainable and bio-based composites [22].

Investment in recycling infrastructure, supportive regulations, and consumer awareness is also accelerating the adoption of environmentally responsible composite solutions [23]. Policy frameworks such as the European Green Deal, the U.S. Infrastructure Investment and Jobs Act, and the UN's SDG roadmap play vital roles in shaping market dynamics [24].

Table 8. Comparison of the recyclability and biodegradability of different polymer composites based on their matrix and reinforcement types

Composite Type	Matrix	Fiber Type	Recyclability	Biodegradability
Thermoset FRP	Epoxy/Polyester	Glass/Carbon	Low	Low
Thermoplastic FRP	PP/PE/PA	Glass/Carbon	Medium	Low
Bio-composites	PLA, PHA, TPS	Hemp/Jute/Flax	High	High
Hybrid Composites	Mixed	Mixed	Medium	Variable

The projected economic growth trends across key composite sectors from 2024 to 2030 are shown in Figure 3.

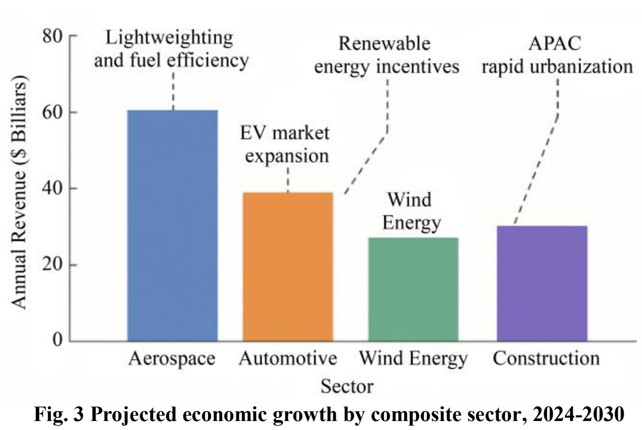

Fig. 3 Projected economic growth by composite sector, 2024-2030

7. Future Prospects

7.1. Need for Green and Bio-based Composites

In line with global sustainability goals, there is increasing demand for bio-based and green composites that offer lower environmental footprints and are derived from renewable sources. While natural fiber composites using flax, hemp, or jute have shown promise, their mechanical properties, moisture absorption tendencies, and inconsistent quality limit their use in structural applications [25-32]. Furthermore, bio-resins based on Polylactic Acid (PLA), Polyhydroxyalkanoates (PHA), and epoxidized soybean oil often lack the thermal and oxidative stability needed for demanding applications [33].

Hybrid systems combining natural fibers with synthetic matrices or using nano-reinforcements such as cellulose nanocrystals or nanoclays are being explored to enhance mechanical and barrier properties. However, challenges related to interfacial bonding, degradation under UV and humidity, and scalability persist [34]. Life Cycle Assessments (LCA) and techno-economic analyses are crucial to identify commercially viable green alternatives that do not compromise performance [35].

7.2. Research Gaps and Opportunities

Despite the growing body of literature on polymer composites, several research gaps remain. For instance, the development of multifunctional composites that integrate structural and sensing capabilities is still in its infancy. Embedding self-sensing, self-healing, or energy-harvesting functionalities into composites opens exciting avenues for smart infrastructure and mobility solutions, but requires cross-disciplinary innovation in materials science, electronics, and data analytics [36].

Another promising frontier is the application of machine learning and artificial intelligence in composite design, manufacturing, and quality control. Data-driven approaches can accelerate the discovery of optimal material formulations, predict failure modes, and automate inspection processes [25]. However, these techniques depend on the availability of large, high-quality datasets and robust validation models. Collaborative platforms and open-access databases are essential to bridge this gap and foster community-driven innovation [28].

Additionally, future research should focus on improving the recyclability of thermoset composites, which currently pose significant end-of-life disposal challenges. Innovative strategies such as dynamic covalent chemistry, vitrimer matrices, and solvolysis offer promising pathways, but require further development and industrial validation [37].

8. Alignment with SDGs and Policy Implications

8.1. Mapping Polymer Composite Applications to Specific SDGs

Polymer composites, with their unique structural and functional properties, offer direct contributions to several Sustainable Development Goals (SDGs), particularly those centered on infrastructure, energy, climate, and innovation. For instance, SDG 9 (Industry, Innovation, and Infrastructure) is advanced through the incorporation of lightweight, durable composite materials in transport and construction sectors, enhancing efficiency and reducing resource usage [38]. Similarly, SDG 7 (Affordable and Clean Energy) is addressed through the use of composites in wind turbine blades, solar panel supports, and energy storage components, all of which demand high-performance materials that can withstand harsh environmental conditions [39].

Further, polymer composites contribute to SDG 11 (Sustainable Cities and Communities) by enabling smart city infrastructures with sensor-embedded materials and lightweight urban mobility systems [40]. Their role in reducing transportation emissions aligns directly with SDG 13 (Climate Action), given that composite applications in electric vehicles and aviation significantly cut fuel consumption and carbon emissions [41]. Table 9 provides an overview mapping specific polymer composite applications to relevant SDGs, illustrating the multifaceted impact of these materials.

Table 9. Mapping of polymer composite applications to relevant SDGs

Application Area	SDG Target Addressed	Impact of Composites
Wind Turbine Blades	SDG 7, SDG 13	Lightweight, durable structures for renewable energy
EV Battery Housings	SDG 9, SDG 13	Safety, thermal insulation, and weight reduction
Smart Building Materials	SDG 11, SDG 9	Insulation, sensors, and energy-efficient construction
Public Transit Systems	SDG 11, SDG 13	Reduced vehicle weight, improved fuel efficiency
Bio-based Composite Packaging	SDG 12, SDG 15	Reduced plastic pollution and environmental impact

8.2. Policy Support for Green Material Adoption

National policies that offer subsidies or tax credits for industries using green composites can significantly accelerate their market penetration [42, 43].

Furthermore, public procurement policies mandating sustainable materials in infrastructure projects-such as bridges, roads, and government buildings-serve as strong demand drivers [44]. Governments can also support research and development through grants, public-private partnerships, and green innovation funds. Regulatory consistency and simplification of certification processes are key enablers for startups and SMEs looking to commercialize innovative composites [45]. Coordinated global policy efforts can establish harmonized standards, enhancing material interoperability and encouraging cross-border innovation and trade [46].

8.3. Industry-Academia-Government Collaboration

Maximizing the impact of polymer composites on sustainable development necessitates strong collaboration between industry, academia, and government. Academia plays a critical role in advancing fundamental research on composite chemistry, mechanics, and degradation behaviors, while industries bring in scalability, market needs, and application-specific challenges [47]. Governments facilitate this synergy by providing the funding mechanisms, regulatory clarity, and policy vision necessary to bridge gaps between research and commercialization [43, 44].

Notable collaborations such as the National Composites Centre (UK), Fraunhofer Institute (Germany), and the Institute for Advanced Composites Manufacturing Innovation (USA) illustrate the success of this tripartite engagement. These hubs are accelerators for composite innovation and training grounds for the future workforce [45, 46]. Collaborative platforms that integrate digital technologies-such as material informatics and AI-driven design tools-further enhance the ability to co-create sustainable, cost-effective, and high-performance composites [47].

9. Conclusion

Enabler of Sustainable Innovation: Polymer composites are critical in advancing sustainable technologies across sectors such as mobility, energy, and infrastructure by offering high performance with reduced environmental impact.

Support for Global SDGs: Their application directly contributes to achieving key UN Sustainable Development Goals, including clean energy (SDG 7), industry and infrastructure innovation (SDG 9), sustainable urban development (SDG 11), and climate action (SDG 13).

Lightweighting and Efficiency Gains: By enabling lighter, stronger, and more corrosion-resistant components, composites significantly reduce energy consumption and enhance the efficiency of vehicles, renewable energy systems, and infrastructure.

Pathway to Circular Economy: The integration of recyclable, biodegradable, and bio-based composites promotes circular economy practices, reducing reliance on fossil fuels and minimizing end-of-life environmental burdens.

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