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REVIEW

Carbon-Based Polymer Composites and Nanocomposites: Innovations and Emerging Trends

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ABSTRACT: Advanced multifunctional materials, Carbon-Based Polymer Composites (CBPCs) have attracted wide attention due to their excellent mechanical, thermal, electrical and barrier properties. Carbon-Based Reinforcements (CBRs) such as Carbon Nanotubes (CNTs), Graphene (GR), Graphene Oxide (GO) and biochar greatly improve the performance of polymer matrices while retaining lightness. The high strength to weight ratio, thermal stability, electrical conductivity and Electromagnetic Interference (EMI) shielding property of these composites have given rise to enormous interest in their use in aerospace, automotive, construction, electronics and biomedical applications. This review is grounded in 106 papers published from 2024 to 2026 and identified from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley, and IEEE Xplore databases following specific selection criteria. Different synthesis and fabrication methods, including hand lay-up, compression moulding, Resin Transfer Moulding (RTM), Additive Manufacturing (AM), electrospinning, melt blending, and *in situ* polymerisation, are critically examined. In addition, mechanical/thermal/barrier/electrical properties and their effects with the carbon fillers are examined in detail, and especially tensile strength, flexural behaviour, thermal conductivity, electrical conductivity, EMI shielding effectiveness and durability. Different carbon reinforcements are compared in terms of performance, sustainability, cost and scalability. Besides, the durability factors, environmental issues, Life Cycle Assessment (LCA) and new industrial applications are presented. Lastly, the problems existing in the field, research gaps, and prospects are identified and discussed with particular focus on sustainable carbon nanomaterials, green manufacturing processes and advanced multifunctional composites. There was an improvement in the composite performance in the reviewed studies. Composites with graphene and CNTs improved their mechanical, thermal, and electrical properties. Carbon fibre composites showed improvement in mechanical and stiffness properties, while biochar composites showed 15–40% improvement in mechanical properties and were more economical and sustainable. Reported performance improvements were interpreted according to the polymer matrix, filler type and loading, processing conditions, and testing methods, ensuring accurate and comparable quantitative claims across the reviewed studies.

KEYWORDS: Carbon nanofillers; mechanical properties; thermal conductivity; interface engineering; hybrid reinforcement; thermal management; sustainable materials

1 Introduction

CBPCs and nanocomposite materials have been identified as one of the most promising advanced materials owing to their remarkable properties [1]. They are created by adding reinforcements of carbon-based materials, such as carbon fibres, CNTs, GR, GO, and biochar, to polymer matrices to improve their properties [2]. The lightweight property, coupled with a high strength-to-weight ratio, good durability, and multifunctionality, has led to the increased use of carbon-based materials in aerospace, automotive, building construction, electronics, and biomedical applications [3]. The capability of these materials to satisfy the increasing demands for advanced and sustainable materials has made them an important research area within materials science and engineering [4].

The use of polymer-based composite materials with carbon fillers increases due to the requirement for materials that provide enhanced performance with a decrease in weight and energy usage [5]. The use of lightweight and high-performance materials has risen rapidly within the aerospace, automotive, and transportation industry [6]. Furthermore, the rising demands for electronics, energy storage systems, and smart materials have been very instrumental in the development of carbonaceous composites [7]. Several factors dictate the properties of these materials, including the kind of fillers employed, the percentage of fillers within the matrix, good dispersion, good interface bonding, and cost [8]. The employment of such fillers has made it possible to develop multifunctional composites capable of meeting the demands of contemporary technological and engineering applications [9]. The recent research interest has been inclined towards improving the fabrication process and interactions.

To improve the characteristics of polymer composites made of carbon-based materials, various manufacturing methods have been extensively examined [10]. Manufacturing methods that are usually employed for making polymer composites include hand lay-up, compression moulding, resin transfer moulding, and filament winding [11]. Modern manufacturing processes, such as melt blending, solution casting, electrospinning, additive manufacturing, and *in situ* polymerization, have also improved the performance of these materials [12]. In addition to these, different techniques such as surface modification, interface engineering, and hybrid reinforcement have been used to enhance the dispersion, adhesion at interfaces, mechanical strength, thermal stability, and electrical conductivity [13]. 3D-printed continuous carbon fiber composites demonstrate rate-dependent mechanical and self-monitoring behavior, with damage evolution, resistance changes, microcracking, and fiber breakage supporting their potential for structural health monitoring applications. Recent developments in BN-based hybrid architectures highlight the benefits of integrating different filler morphologies. A dual-path architecture comprising BN nanoribbons and BN nanosheets achieved a thermal conductivity of 3.12 W m^{-1} K^{-1} at a BN loading of 14 wt%, while maintaining 82% filler recyclability. These findings indicate that combining different filler morphologies with interfacial functionalization can promote more efficient thermal-conduction pathways than single-filler configurations while improving the recyclability of the composite system [14].

Although there have been substantial advancements, problems such as the need for proper nanofiller dispersion, improved durability, an effective and low-cost manufacturing process, and full-scale production still exist. While there have been many advancements made in carbon-polymer composite technology, the vast literature that continues to increase through 2024–2026 is still scattered in terms of reinforcement type, manufacturing process, interfacial modification methods, material functionalities, sustainability, and application areas. For this reason, a systematic review on the comparison of the developments and analyzing current trends together with the challenges encountered in dispersion, interface bonding, scalability, cost, and sustainability is necessary at this point.

Challenges and Research Gaps

Despite recent advances, CBPCs still face challenges related to nanofiller dispersion, interfacial bonding, durability, processing complexity, cost, and large-scale manufacturing. Differences in matrix type, filler concentration, processing conditions, and testing methods also limit direct comparison of reported results. Furthermore, integrated evaluations of performance, sustainability, recyclability, scalability, and environmental impact remain limited, highlighting important gaps for systematic investigation.

In order to solve these problems, this review offers a detailed examination of recent developments and trends in carbon-based polymeric composites and nanocomposites. These include different types of CBRs, manufacturing methods, ways to improve material properties, comparisons of performance, durability, and applications in industry. Moreover, recent advancements in smart materials, sustainable nanomaterials, hybrid reinforcements, and AI-enabled material development have also been considered. This review can be of great help in the further development of carbon-based composite materials. The primary contribution of the paper is shown below,

- Analyse recent developments in CBPCs and nanocomposites, focusing on carbon fibres, CNTs, GR, GO, and biochar as reinforcing materials.
- Evaluate the effects of processing technologies, functionalization techniques, and interface engineering on the mechanical, thermal, electrical, and barrier properties of CBPCs.
- Compare different carbon-based composites in terms of performance, sustainability, cost, scalability, and potential application areas.
- Identify current research challenges and knowledge gaps and highlight future research opportunities for advanced and sustainable carbon-polymer composites.

The rest of this paper is arranged as follows. In Section 2, the methodology of carrying out the systematic review is presented; the process of literature search and the selection criteria for studies according to PRISMA are discussed. Section 3 contains basic facts on CBPCs. In Section 4, the methods of synthesis and fabrication of CBPCs are explained. The mechanical properties of CBPCs, such as tensile strength, flexural properties, and impact resistance, are discussed in Section 5. Functional properties of CBPCs, such as thermal, electrical, and barrier properties, are covered in Section 6. The comparative analysis is described in Section 7. Durability and Environmental issues are mentioned in Section 8. The applications are reviewed in Section 9, while the challenges and gaps in the research are considered in Section 10. Future Directions are provided in Section 11. Finally, conclusions are drawn in Section 12.

The overall structure of the carbon polymeric composites is shown in Fig. 1. Various kinds of carbon fillers, such as carbon fibre, CNTs, GR, GO, and biochar, have been added to the polymer matrix to form composite materials by different means. The composites exhibit enhanced behaviour in terms of their mechanical, thermal, electrical, barrier, and durable properties for use in aerospace, automotive, building and construction, electronic, and biomedical industries.

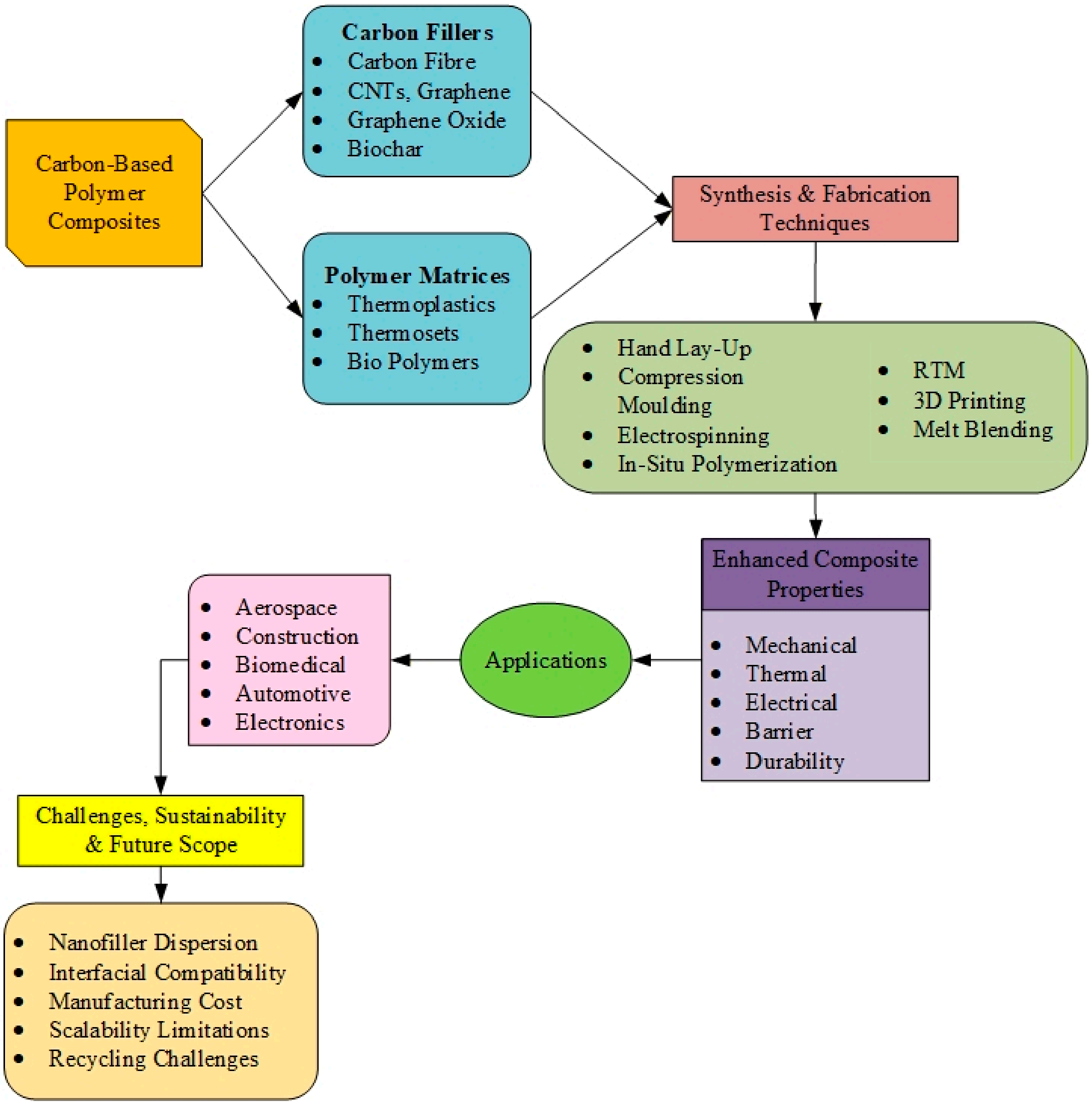

Figure 1: Overview of Carbon-Based Polymer Composites Showing Reinforcement Types, Enhanced Properties, Processing Approaches, and Major Applications.

2 Methodology

2.1 Literature Search Strategy

A systematic review of literature was conducted using online databases such as Scopus, Web of Science, Science Direct, IEEE Xplore, Springer Link, and Wiley Online Library. Key terms used for searches include carbon-based polymer composite materials, carbon fibre, CNTs, GR, GO, biochar, and properties of composites. Searches were conducted for publications between 2024 and 2026.

2.2 Inclusion and Exclusion Criteria

Peer-reviewed journal papers from 2024 to 2026 have been utilized to identify current developments related to carbon-polymer composite materials. The selection of literature sources was based on their pertinence to materials, preparation methods, properties, applications, and sustainability issues. Quality assessment involved evaluating the source's prestige and relevancy in relation to the purpose of this review.

Conference papers, books, patents, duplicate entries, non-English language publications, and out-of-scope articles have been omitted. Literature search was done through Boolean searching techniques specific to each database, with pre-defined search dates and a publication period of 2024–2026. The resulting citations were evaluated for eligibility via title and abstract screening, while those that passed through that step were subjected to a full-text evaluation against predetermined inclusion and exclusion criteria. The methodological quality and potential risks of bias were evaluated among included studies based on methodological clarity, completeness of reporting, and relevance to review objectives.

2.3 Study Selection Process

PRISMA was used to guide the systematic process of screening the articles for inclusion. First, duplicates were removed, then the titles, abstracts, and full texts were reviewed. In total, based on the inclusion criteria, 106 articles were included for the qualitative analysis.

The PRISMA study selection strategy is illustrated in Fig. 2. To start with, a total of 1200 references were sourced from different databases. After the exclusion of 240 duplicates, there were 960 studies left for screening based on their titles and abstracts. In this stage, 760 references were screened out due to failing to meet the inclusion criteria. Of the remaining 200 full-text references, 94 articles were excluded owing to the following reasons: lack of adequate data, irrelevance, non-English publications, conference articles, and duplicates. The final number of articles that met all inclusion criteria and therefore were included in this systematic review was 106.

2.4 Data Extraction and Analysis

The relevant data, such as the type of reinforcement, polymer matrix, method of manufacture, properties, durability, and applications, were obtained from the studies. The data were classified based on material types, processes, properties, applications, and sustainability issues. Qualitative comparative analysis was conducted in order to establish significant trends, performances, limitations, and areas for further investigation in the field of carbon polymer composite materials.

3 Fundamentals of Carbon-Based Polymer Composites

3.1 Constituents of Carbon-Based Polymer Composites

CBPCs are considered highly sophisticated materials that have been produced using a mixture of a polymer matrix and carbon-based fibres. Current research has revealed that adding carbon nanoparticles to the material leads to improved composite characteristics and allows such materials to be used in the field of aerospace, automotive, electronics, and the energy industry [15]. Moreover, carbon-based polymer nanocomposites possess excellent electromagnetic shielding properties [16].

The main components of these composites are the polymer matrix and CBRs. In these materials, the polymer matrix serves as the continuous phase which acts as a structure for the reinforcement phase. Engineered carbon structures, known for their special bonding properties, have been proven effective for improving the efficiency of these composites [17]. Porous CBPCs are also known for their gas separation capability and environmental friendliness [18].

Carbon-containing reinforcing agents can be obtained in various forms, including carbon fibres, CNTs, GR, GO, fullerenes, activated carbon, and biochar. Such materials possess unique characteristics like superior strength, low density, excellent conductivities, and high surface area.

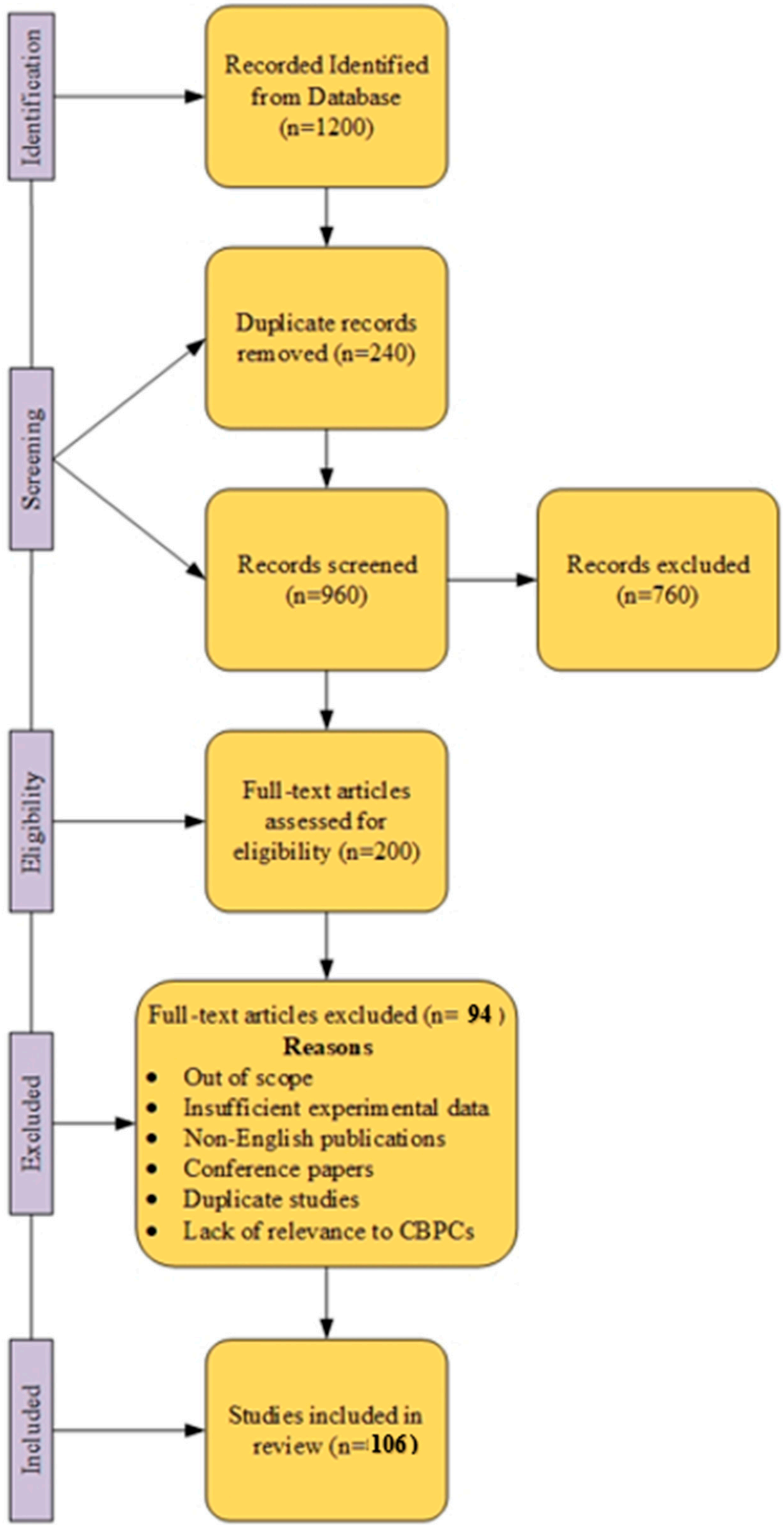

Figure 2: PRISMA Flow Diagram Showing the Literature Identification, Screening, Eligibility Assessment, and Final Study Selection Process.

The developments that have been made in AM technologies have enabled the manufacture of complex carbon-filled composite materials with improved structure and performance [19].

The great advantage of CBPCs can be associated with synergistic effects between the matrix polymer and the carbon reinforcements. Such a material class has significant benefits for their mechanical, thermal, electric, and multifunctional properties [20]. Among all other reinforcements, CNTs have been given special attention because of their unique properties, although there are problems with dispersion and interfacial adhesion [21].

3.2 Types of Carbon-Based Reinforcements

Carbon-based reinforcing agents are critical for improving the mechanical, thermal, and electrical properties of polymeric composites. Some common reinforcing materials used are carbon fibres, CNTs, GR, GO, Graphene Nanoplatelets (GnPs), and other carbon-based nanoparticles. The unique properties of each reinforcement are important for designing advanced composite materials for different industries such as aerospace, automotive, electronics, and energy.

Table 1 provides information about the important types of CBRs utilized for making polymer composites. The table gives a brief idea of the significant characteristics of these materials, as well as their strengths and uses. The disparities in dimensionality, functionality, reinforcing efficiency, and applicability among the different CBRs. The data thus generated can be used to determine the most suitable reinforcement based on the needed mechanical, thermal, electrical, and structural characteristics of the composite.

Table 1: Types, Structural Characteristics, Key Properties, Advantages, and Applications of Carbon-Based Reinforcements Used in Polymer Composites.

Reinforcement Type	Dimensionality	Key Properties	Major Advantages	Typical Applications	Ref.
GnPs	2D Nanosheet Structure	Enhanced mechanical and thermal properties	Improved reinforcement efficiency	Biopolymer composites	[22]
Carbon Fibres	1D Fibrous Structure	High strength and impact resistance	Excellent structural reinforcement	Flexible composite structures	[23]
Hybrid Carbon Reinforcements	Multi-scale Structure	Synergistic mechanical enhancement	Combined reinforcement effects	Cement-based composites	[24]
GO	2D Nanosheet Structure	Improved mechanical properties	Enhanced interfacial interaction	Rubber blend composites	[25]
Carbon-Based Nanoparticles	0D Nanoscale Particles	Enhanced microstructure and strength	Improved coating performance	Epoxy coatings	[26]
Carbon Fibres	1D Fibrous Structure	High strength and durability	Effective reinforcement capability	Cementitious composites	[27]
CNTs	1D Tubular Nanostructure	Electrical conductivity and sensing capability	Multifunctional reinforcement	Smart cement composites	[28]
GnPs	2D Layered Structure	Thermal, electrical, and tribological performance	Improved multifunctionality	Conductive composites	[29]
GFRP Reinforcement	Fibrous Structure	Structural strengthening	Enhanced shear performance	Reinforced concrete beams	[30]

3.3 Composite Classification

The categorisation of carbon polymer composites depends on the nature, size, and distribution used in their production. The various categorizations have different characteristics and thus are used for varied purposes such as structural components, sensors, electrical applications, and many others. It is important to understand these categorizations to choose the appropriate composite for a particular use.

Table 2 categorizes the carbon-based polymer composite materials based on the reinforcing materials used and the properties exhibited by the materials. The main focus of this classification is the versatility of the functions served by the carbon-based reinforcing materials, which include structure reinforcement, sensing, and conductivity, among others.

Table 2: Classification of Carbon-Based Polymer Composites According to Reinforcement Type, Matrix, Structure, and Functional Characteristics.

Composite Category	Reinforcement Type	Key Characteristics	Representative Applications	Ref.
Carbon Fibre-Reinforced Polymer Composites (CFRPs)	Carbon Fibres	High strength and damage resistance	Aerospace and structural components	[31]
Conductive Polymer Composites	Conductive carbon particles	Enhanced electrical conductivity and percolation behaviour	EMI shielding and electronic devices	[32]
Doped Polymer Composites	Carbon fillers with metal complexes	Improved optical and electrical properties	Optoelectronic applications	[33]
Particle-Reinforced Polymer Composites	Carbon nanoparticles and bitumen fillers	Enhanced structural and morphological properties	Coatings and industrial materials	[34]
Hybrid Polymer Composites	CNTs and Fe fillers	Multifunctional mechanical and magnetic properties	Smart materials and advanced manufacturing	[35]
Polymer Nanocomposites	Nanoscale carbon fillers	Improved elastic and functional performance	High-performance engineering materials	[36]
Carbon Fibre-Reinforced Polymer Composites (CFRPs)	Carbon Fibres	Enhanced impact resistance and structural reliability	Automotive and aerospace structures	[37]
Carbon Nanotube-Reinforced Composites	Multiwall Carbon Nanotubes (MWCNTs)	High conductivity and sensing capability	Flexible sensors and wearable electronics	[38]

3.4 Reinforcement–Matrix Interactions in Carbon-Based Polymer Composites

The behaviour of carbon-polymer composite materials is primarily governed by the interfacial properties between the reinforcement and matrix materials. The interface acts as an important parameter for stress transfer and dispersion of the filler material, improving composite performance [39].

Carbonaceous filler materials, like MWCNTs, graphite, and hybrid filler materials, increase the mechanical, electrical, and functional characteristics of polymer composites through efficient matrix adhesion [40]. Also, carbon nanotube-filled dynamic polymer networks show better self-healing and structural performance owing to improved reinforcement-matrix interaction [41].

Incorporating sustainable carbon-based materials, such as biochar, into filler materials helps improve the properties of the composites due to increased compatibility [42]. For fibre-reinforced composites, the orientation, volume, and bonding of fibres play important roles in determining their impact strength and ability to transfer loads [43]. The design of optimized interfaces is vital for increasing heat transfer in polymer nanocomposites [44].

Charcoal-reinforced composites have better thermal, physical, and microstructural properties because of improved filler-matrix interaction [45]. Moreover, carbon nanotube addition enhances the mechanical and tribological behaviour of fibre-reinforced composites because of improved interfacial bonding [46]. Advanced composite structures of carbon fibres have exhibited good performance for electromagnetic shielding [47], while biofibre-reinforced carbon composites have good potential for electromagnetic shielding for aerospace applications [48].

3.5 Structure–Property Relationships of Carbon-Based Polymer Composites

CBPCs' characteristics are largely determined by structural factors, such as the types of reinforcing materials and filler arrangements. Structural design can help make substantial advancements in various performances, such as mechanical, electrical, thermal, and functional performances [49].

Incorporation of carbon fibres into composite materials has increased strength, stiffness, and durability through effective load transfer [50]. Parameters involved in manufacturing processes and the configuration of structures are equally important in deciding the mechanical behaviour of such composite structures [51]. Moreover, machine learning techniques have also been used for the prediction of the bending properties of polymers [52].

Carbon-reinforced structures play an important role in electrochemical and electromagnetic systems. Composites of polymers and carbon show good energy storage capacity in supercapacitor applications [53]. The arrangement of carbon-based structures plays an important role in electromagnetic wave attenuation and absorption [54].

High concentration and dispersion of carbon fillers significantly influence the electrical and dielectric performance of polymer-based composites. Improved electrical and dielectric performances have been observed in activated carbon-filled composites [55]. In addition, GO-based polymer composites demonstrate good structure, morphology, and optoelectronic performances owing to better microstructural attributes [56]. Table 3 summarizes the key structural parameters and their influence on composite properties. Composite performance is influenced by structural parameters based on type, density, distribution, interface bonding, orientation, structure, porosity, flaws, and microstructure. All these parameters together have an effect on strength, thermal stability, electrical conductivity, and multifunctionality.

Table 3: Key Structural Parameters and Their Effects on the Mechanical, Thermal, Electrical, and Durability Properties of Carbon-Based Polymer Composites.

Structural Parameter	Description	Affected Properties
Reinforcement Type	Type of carbon filler (carbon fibres, CNTs, GR, GO, biochar)	Mechanical, thermal, and electrical properties
Filler Concentration	Amount of reinforcement incorporated into the matrix	Strength, conductivity, and dielectric behaviour
Filler Dispersion	Distribution of fillers within the polymer matrix	Load transfer efficiency and durability
Interfacial Bonding	Adhesion between reinforcement and polymer matrix	Mechanical strength and thermal stability

Table 3: *Cont.*

Structural Parameter	Description	Affected Properties
Reinforcement Orientation	Alignment of fibres or nanofillers	Stiffness and impact resistance
Composite Architecture	Layered, hybrid, or nanocomposite configuration	Multifunctional performance
Porosity and Defects	Presence of voids and imperfections	Structural reliability and durability
Microstructure	Internal morphology and phase distribution	Optical, thermal, and electrical properties

4 Synthesis and Fabrication Techniques

The process of synthesis and manufacturing that is used for making CBPCs is extremely important for the development of the microstructure of these materials, the proper dispersion of reinforcement, as well as interfacial bonding. Both classical and modern approaches to manufacturing are applied for obtaining high-performance CBPCs. It is necessary to select the correct method of manufacturing for CBPCs to obtain the required results.

Table 4 describes the widely employed process and fabrication methods that are utilized in making carbon polymer composites and their composite systems, and the important benefits associated with them. The choice of the processes is critical for enhancing composite performance.

Table 4: Synthesis and Fabrication Techniques, Composite Systems, and Key Performance Advantages of Carbon-Based Polymer Composites.

Fabrication Technique	Composite System	Key Advantages	Ref.
Hand Lay-Up	Carbon Fabric-Reinforced Polymeric Composite	Improved tensile strength, lightweight structure, and enhanced load-bearing capability	[57]
Hand Lay-Up and Compression Moulding	Biodegradable Hybrid Fibre-Reinforced Sandwich Composite	Improved mechanical performance, lightweight design, and environmental sustainability	[58]
RTM	Epoxy-Based Composite	Uniform resin distribution and reduced void formation	[59]
Electrospinning	Carbon Black–PAN/Nickel Foam Composite	Production of ultrafine nanofibers with high surface area	[60]
3D Printing of Nanocomposites	Graphitic Nanofiller-Reinforced PLA Composite	Design flexibility and multifunctional properties	[61]
Nanofiller Reinforcement Processing	MWCNT-Reinforced Glass Fibre Composite	Improved mechanical performance and failure resistance	[62]
FGF 3D Printing	CNT-modified basalt fiber/PA6 composite	Improved tensile and flexural properties, strong interfacial interaction, and reduced warping	[63]

5 Mechanical Property Enhancement

Enhancement of mechanical properties is one of the main goals pursued during the fabrication of CBPCs. Use of CBRs like CNTs, GR, carbon fibres, and nanocomposites enhances the mechanical properties of the polymers, such as strength, rigidity, toughness, impact resistance, and durability. The above factors contribute to enhanced mechanical performance due to effective stress transfer, high bonding at the interface between the polymer matrix and reinforcing particles, and proper dispersion of fillers in polymer matrices.

The important reinforcement techniques for increasing the mechanical properties of composite materials are illustrated in Table 5. The different types of carbon reinforcements and mixed reinforcements increase the tensile strength, flexural strength, toughness, stiffness, impact strength, and adhesion strength. Reinforcement engineering plays an important role in composite development.

Table 5: Carbon Reinforcements, Composite Systems, and Their Effects on the Mechanical Properties of Carbon-Based Polymer Composites.

Reinforcement Material	Composite System	Mechanical Property Enhancement	Ref.
CNT-modified basalt fibres	Basalt fibre/nylon 6 composite fabricated by FGF 3D printing	Improved tensile and flexural properties due to enhanced interfacial interaction	[63]
GO and Reduced Graphene Oxide (rGO)	Epoxy Nanocomposite	Improved tensile and flexural strength	[64]
Structural Optimization Approach	Battery Pack Composite Structure	Enhanced impact resistance and fatigue endurance	[65]
Nano- and Micro-Scale Reinforcements	Polymer Matrix Composite	Improved mechanical property estimation and performance	[66]
CNTs and GnPs	Epoxy Nanocomposite	Enhanced strength, stiffness, and mechanical stability	[67]
Functionalized Boron Nitride Nanosheets	Thermal Interface Composite	Enhanced interfacial strength and structural performance	[68]
MWCNT-Grafted Aramid Fibres	Epoxy Composite	Improved interfacial interaction and mechanical properties	[69]
Hybrid Polypropylene Fibres	Concrete Composite	Improved mechanical strength and crack resistance	[70]
Nanostructured resin matrix and hybrid fibre networks	Biomimetically engineered FRP composite	Enhanced mechanical strengthening through hierarchical architecture and improved interfacial interactions	[71]

6 Functional Properties of Carbon-Based Polymer Composites

6.1 Thermal Properties

Thermal conductivity is one of the most important functional properties of carbon-filled polymer composites. The addition of carbon fibres, graphene, and CNTs increases the rate of heat flow by forming conductive pathways within the composite matrix. It was observed by Lu et al. [72] that the incorporation of graphene networks together with vertical alignment of carbon fibres improves thermal conduction by lowering thermal resistance.

Nanocomposites made from CNTs possess enhanced fire-resistance and thermal stability characteristics [73]. Likewise, bio-based composites made from microencapsulated CNTs have superior thermal conductivities for thermal management purposes [74].

The silicon-containing polymer nanocomposites are more thermally stable at high temperatures [75]. The combination of boron nitride and GR filler in a single composite material provides higher thermal conductivity along with electrical insulation [76]. The development of composites having dual functionality in thermal conduction and microwave absorption shows advanced thermal properties [77]. In addition, flax-carbon-Kevlar composite materials possess better thermal properties [78].

Table 6 shows the main thermal characteristics of carbon-reinforced polymers and their importance in determining material behaviour. These carbon-based materials play a role in heat dissipation, heat stability, fire resistance, and dimensional stability, which makes these materials ideal for use in thermal and high-temperature applications. The thermal properties of CBPCs include thermal conductivity, stability, flame retardancy, heat resistance, dimensional stability, and thermal management. Carbon reinforcements improve heat transfer, thermal durability, fire resistance, structural stability, and efficient heat regulation under elevated-temperature conditions.

Table 6: Major Thermal Properties of Carbon-Based Polymer Composites and the Contributions of Carbon-Based Reinforcements.

Thermal Property	Role in Composites	Contribution of CBRs
Thermal Conductivity	Facilitates heat dissipation and transfer	Creates efficient thermal conduction pathways
Thermal Stability	Maintains performance at elevated temperatures	Enhances resistance to thermal degradation
Flame Retardancy	Reduces flammability and heat release	Improves fire resistance and combustion delay
Heat Resistance	Withstands prolonged thermal exposure	Increases durability under thermal stress
Dimensional Stability	Maintains structural integrity during heating	Minimizes thermal expansion and deformation
Thermal Management Capability	Controls heat accumulation in devices and structures	Enables efficient thermal regulation

6.2 Electrical Properties

Electrical properties stand out as some of the most important functional properties exhibited by CBPCs due to their use in the development of electrically conducting materials, EMI shielding structures, sensors, and bioelectronics. Carbon-based fillers improve electrical conductivity through the formation of a conductive network structure within the polymer matrix [79].

Conductive hydrogels based on carbon display outstanding conductivity, flexibility, and biocompatibility features, which render them ideal for bioelectronic interface purposes [80]. Furthermore, thin-film composite membranes have also been found to possess enhanced charge and functional performance attributes, thus emphasizing the possibility of using more complex polymer composite structures for electrical purposes [81]. Hybrids of filler and polymer-based composites also enhance multi-functionality features through better conductivity attributes [82].

The electrical performance of carbon fibre-based composite materials could also be enhanced by surface treatment with nanostructured materials to obtain increased conductivity and functionality [83]. Functionalized conducting polymer-based nanocomposites have also proven promising in applications such as supercapacitors and biological sensing devices [84].

Furthermore, CNT-based polymer composites are widely employed in sensing applications due to their excellent piezoresistive behaviour. Flexible CNT composites have demonstrated effective human motion monitoring capabilities [85], while 3D-printed CNT-based composites exhibit reliable strain-sensing performance for smart sensing systems [86].

Noted that g-C_3N_4/LSR composites show nonlinear electrical conductivity with the effect of filler concentration and microstructure. Oxygen doping makes the materials show more nonlinearity at lower filler concentrations without altering their thermal conductivity [87].

Table 7 compares the various network structures used to enhance thermal conductivity in carbon-based polymer composites. The roles of filler loading, filler interactions, and interface interactions have been highlighted. The new BN-based systems have shown improvement in heat transfer routes due to segregation, magnetization, and 3D networks. The comparison clearly indicates that optimization of network structure and interface interactions is a key factor for obtaining high thermal conductivity without increasing filler loadings.

Table 8 describes the filler content, percolation point, connectivity, and interfacial thermal resistance. SEM, TEM, and EDS characterization techniques are also indicated for the evaluation of filler dispersion and structural homogeneity. Statistical indicators including average ± SD and sample size ensure the reproducibility of properties. Thermal and mechanical properties are provided.

Table 7: Comparison of Network Architecture, Filler Loading, and Thermal Conductivity in Carbon-Based Polymer Composites.

System	Network/ Architecture	Heat-Transfer Mechanism	Loading	Thermal Conductivity	Key Advantage/ Trade-Off
BNNS–graphene/PEG (baseline)	Interconnected hybrid network	Graphene bridges BNNS platelets	10 vol%	2.45 W m^{-1} K^{-1}	Good thermal transport and electrical insulation
BNNS/PVA film	Segregated BNNS network	Enhanced BNNS–BNNS contacts	40 wt%	5.2 W m^{-1} K^{-1}	High conductivity; complex processing
BN/epoxy	Magnetically aligned 3D network	Improved network continuity	25 wt%	229% enhancement	Directional transport; magnetic processing required
3D BN/PDMS	Binder-free 3D BN skeleton	Direct BN–BN heat pathways	40.70 vol%	3.889 W m^{-1} K^{-1}	Continuous network; complex fabrication
CBPCs reviewed	Hybrid, aligned, interconnected networks	Interface and filler–filler interactions	Varies	Varies	Network architecture and interface are important beyond filler loading

Table 8: Mechanistic and Statistical Parameters for Evaluating Thermal and Mechanical Performance of CBPCs.

Assessment Parameter	What Should Be Extracted/Reported from Literature	Mechanistic Significance
Filler loading	Filler concentration (wt% or vol%) and corresponding thermal conductivity	Identifies loading-dependent improvement and optimum filler content
Percolation threshold	Estimated critical filler concentration, φc, where a continuous filler network is formed	Indicates the onset of an interconnected heat-transfer network
Network connectivity	Dispersed, partially connected, interconnected, or 3D network	Explains the formation of efficient thermal pathways
Interfacial modification	Functionalization, coupling agents, surface treatment, polymer–filler interactions	Reduces interfacial thermal resistance and improves heat transfer

Table 8: *Cont.*

Assessment Parameter	What Should Be Extracted/Reported from Literature	Mechanistic Significance
Interfacial thermal resistance	Reported/calculated Rk, where available	Quantifies the thermal resistance at the polymer–filler interface
Microstructure	SEM/TEM images with scale bars and multiple fields of view	Evaluates filler dispersion, agglomeration, orientation, and network uniformity
Elemental distribution	EDS elemental mapping, where available	Confirms spatial distribution and compositional homogeneity
Thermal conductivity	Mean ± SD, number of specimens (n), and measurement method	Establishes reproducibility and reliability of thermal performance
Mechanical properties	Mean ± SD, n ≥ 5 were reported	Establishes statistical reliability of mechanical enhancement
Statistical significance	Standard deviation, confidence interval, or significance testing where available	Distinguishes genuine improvement from experimental scatter
Structure–property relationship	Filler loading → dispersion/network → interface → thermal/mechanical property	Provides the polymer-physics mechanism behind the observed performance

6.3 Barrier Properties

The barrier characteristics play an important role in increasing the durability of CBPCs. The barrier characteristics can decrease the effects of moisture uptake, gas permeation, and deterioration of materials [88].

NFPRPs are characterized by better moisture resistance and environmental stability [89]. The polymer composite coating offers excellent protection against corrosion in aggressive environments [90]. Carbon-based filler material increases the corrosion resistance [91].

Gas barrier efficiency in composites is significantly affected by filler-matrix interactions and membrane morphology. It was found that carbon fibre composites show better gas barrier due to improved interface properties [92]. Composite electrodes improve gas transport performance in energy-related applications [93]. Carbon-based porous structures help in improving gas transport performance [94]. Nanocomposite membranes containing CNTs show improved gas separation efficiency [95]. Polymer membranes incorporating porous structures improve gas separation efficiency due to a diffusion-controlled process [96]. Moreover, composite microporous layers regulate gas transport and minimize oxygen transport resistance in fuel cells [97].

7 Comparative Analysis of Carbon-Based Polymer Composites

Comparative analysis is used to judge the performance and appropriateness of carbon polymer-based composite materials for use in various fields. The effect of different carbon reinforcements, including carbon fibres, CNTs, GR, GO, and biochar, on the physical properties of the material varies. Some of the benefits associated with carbon fillers include improved mechanical properties, heat dissipation ability, electrical conductivity, and EMI shielding capability, whereas bio-based materials add to the environmental sustainability aspect. In addition to that, production costs and industry viability are some of the other major considerations when choosing the right material. Rankings of 1–10 were assigned based on predetermined criteria through the normalization of reported values of the reviewed articles. For mechanical performance, tensile strength, stiffness, toughness, and load transfer were assessed, while sustainability and scalability included renewability, environmental effects, economic value, recyclability, and industrial feasibility. Normalization of values was then converted into a 1–10 scale utilizing the same scoring system for carbon reinforcement in general. Processing conditions significantly affect the dispersion, alignment, networking, and microstructure of the carbon-based polymer composite materials. Microstructural characteristics, along with the interaction between the filler and polymer interface, control stress transfer, heat, and electrical conductivity, as well as the barrier properties. Hence, proper processing, good filler dispersion, and effective interface interaction are crucial in obtaining enhanced material characteristics.

Table 9 is presented to provide an outline of the research topics addressed within the field of CBPCs and nanocomposites. Research papers included in this review are classified according to various criteria such as types of reinforcing materials, types of composites, processing techniques, property improvements, new applications, and sustainability concerns. It should be noted that CBRs have been found to impart a wide range of improved properties to polymeric matrices.

Table 10: A comparative analysis of the sustainability and scalability of various carbon-based fillers based on 5 important criteria is presented. Environmental impact, recyclability, economic viability, energy requirements, and scalability are assessed on a scale of 1 to 5. Biochar/activated carbon demonstrates the most favorable profile among all, while CNTs demonstrate comparatively low values.

Fig. 3 illustrates a qualitative ranking of the mechanical properties of CBRs. A score from 1 to 10 was given to each material according to the literature-based trend in terms of tensile strength, stiffness, toughness, and efficiency in load transfer. Carbon fibres gained the highest relative ranking due to their excellent structural reinforcement properties, followed by CNTs and GR. GO and biochar ranked lower in terms of mechanical performance; however, they have higher sustainability and lower-cost synthesis processes. The ranking is literature-based and qualitative and is used for comparison purposes only.

Fig. 4 depicts a qualitative ranking of the sustainability and scalability of CBRs. Values between 1 and 10 have been provided based on the trends of renewability, environmental friendliness, cost of production, recyclability, and industrial applicability of CBRs. Biochar has received the highest value due to its renewability and environment-friendliness, while graphene and CNTs received relatively lower values due to their higher cost of production and scalability issues. The above values depict only the qualitative comparison of sustainability and cannot be considered as a sustainability index or LCA.

Table 9: Comparative Overview of Carbon-Based Reinforcements, Composite Types, Fabrication Methods, Enhanced Properties, Applications, and Sustainability.

Category	Subcategory	Key Characteristics	Representative References
CBRs	Carbon Fibres	High strength, stiffness, and structural reinforcement	[18,22,34,38,78]
	CNTs	Excellent mechanical, thermal, and electrical properties	[15,19,30,62,83]
	GR and GO	Enhanced conductivity, mechanical performance, and multifunctionality	[16,41,47,58,73]
	Biochar and Activated Carbon	Sustainable and cost-effective reinforcement materials	[33,36,46,92,98]

Table 9: *Cont.*

Category	Subcategory	Key Characteristics	Representative References
Composite Classification	Fibre-Reinforced Composites	Carbon fibres embedded in polymer matrices for structural applications	[22,28,34,78,99]
	Particle-Reinforced Composites	Carbon nanoparticles dispersed within polymer matrices	[24–26,47,93]
	Hybrid Nanocomposites	A combination of multiple reinforcements for multifunctional properties	[26,31,62,77,86]
Fabrication Techniques	Conventional Methods	Hand lay-up, compression moulding, RTM, filament winding	[48–51]
	Advanced Manufacturing	3D printing, electrospinning, melt blending, *in-situ* polymerization	[52–56]
Performance Enhancement	Mechanical Properties	Tensile strength, flexural strength, toughness, impact resistance	[58,62,65,70,82]
	Thermal Properties	Thermal conductivity, stability, and flame retardancy	[68,71,83,86,89]
	Electrical Properties	Conductivity, EMI shielding, sensors, and smart devices	[78,82,93,100,101]
	Barrier Properties	Moisture resistance, corrosion protection, and gas barrier performance	[91,93,102]
Emerging Applications	Energy Storage	Batteries, supercapacitors, and fuel cells	[44,94,100]
	Sensors and Smart Systems	Strain sensors, wearable electronics, and monitoring systems	[87,93,101,103,104]
	Aerospace and Automotive	Lightweight structural and EMI shielding applications	[38,39,78,81,99]
Sustainability and Scalability	Sustainable Materials	Bio-based fillers, recycled carbon materials, and green composites	[33,87,98,105]
	Industrial Scale-Up	Cost-effective manufacturing and commercial feasibility	[56,100]

Table 10: Comparative Analysis, specifically after the discussion comparing the performance and sustainability of different CBPC fillers.

Filler	Environmental	Recyclability	Economic	Energy*	Scalability	Overall
Carbon fibre	3	3	3	2	5	3.2
CNTs	2	2	2	1	3	2
Graphene/GO	3	3	2	2	3	2.6
Biochar/AC	5	4	5	4	5	4.6
BN/BNNS	4	3	2	2	3	2.8

Note: Scores use a 1–5 scale for each criterion, where 5 is the best rating. *The energy score reflects the energy needed to produce the filler. Its scale runs in reverse, so a higher score means lower energy demand. The Overall column gives the simple mean of the five criterion scores.

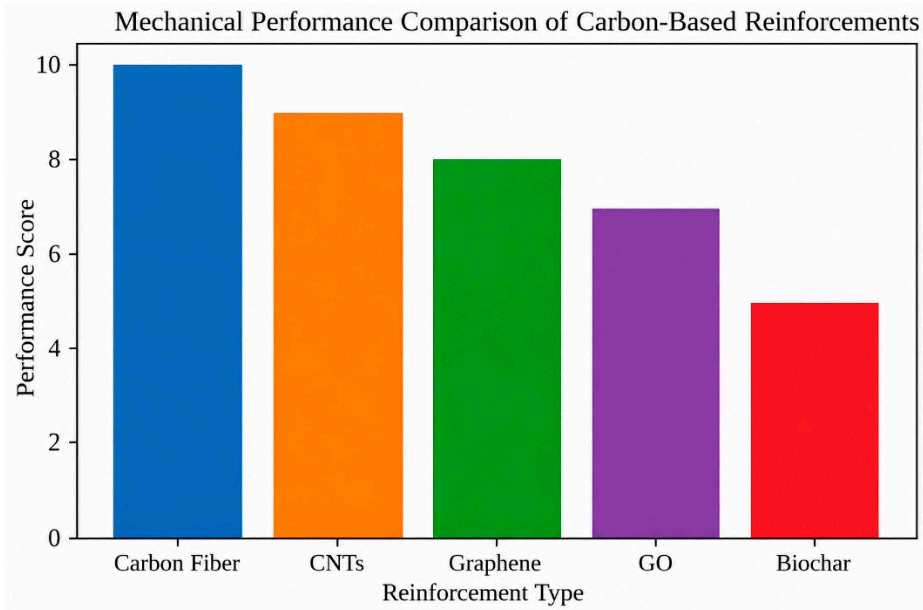

Figure 3: Comparative Mechanical Performance of Carbon-Based Reinforcements Based on Tensile Strength, Stiffness, Toughness, and Load-Transfer Capability.

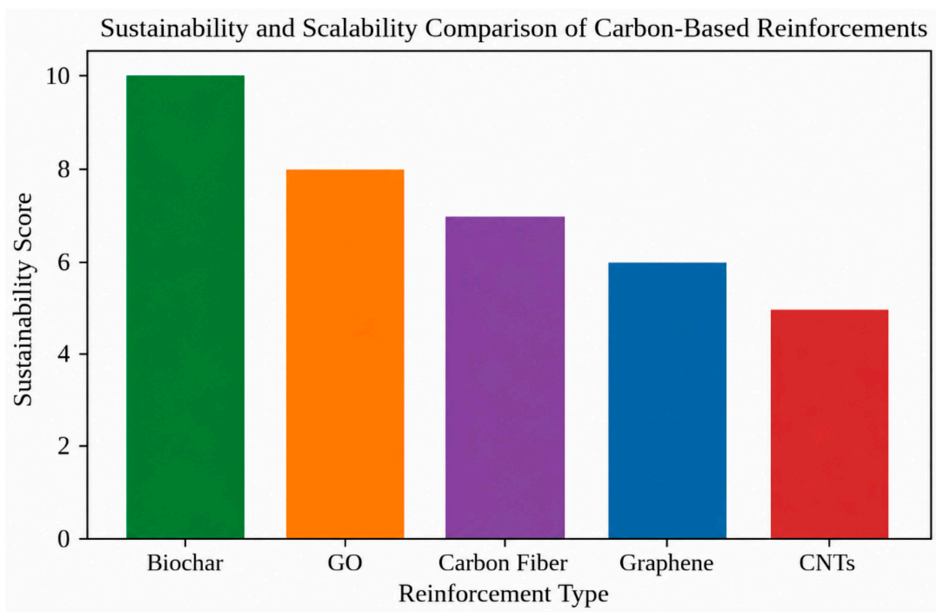

Figure 4: Comparative Sustainability and Scalability of Carbon-Based Reinforcements Based on Renewability, Environmental Impact, Cost, Recyclability, and Industrial Feasibility.

8 Durability and Environmental Considerations

The durability of the material and the effect on the environment are essential factors for the performance of CBPCs. The following aspects may affect their long-term performance: the effect of ultraviolet light, moisture uptake, thermal ageing, and chemical effects. On the other hand, the use of recyclable composites, biopolymers, eco-friendly synthesis techniques, and LCA allows achieving greater sustainability.

Table 11 provides a summary of studies related to durability and sustainability issues of composite materials. The findings reveal progress in environmental stability, corrosion resistance, thermal stability, recycling potential, and the use of bio-materials. Green fabrication techniques and LCA facilitate sustainable composite production.

Table 11: Durability and Sustainability Characteristics of Carbon-Based Polymer Composites, Including Environmental Stability, Recyclability, and Long-Term Performance.

Aspect	Material/System	Key Outcome	Ref.
Environmental Stability	Conductive Rubber Composite	Demonstrated excellent mechanical strength, environmental stability, and electrical conductivity	[99]
Corrosion Resistance	GR-Based Nanocomposite Coating	Improved corrosion protection and durability in automotive applications	[100]
Bio-Based Materials	Starch Bioplastic Composite	Developed sustainable and biodegradable packaging materials	[101]
Thermal Aging	Resin–Polymer Composite System	Thermal ageing significantly influenced bonding performance and durability	[103]
Flame Retardancy and Environmental Adaptability	Hierarchical Polymer Structure	Enhanced flame resistance and adaptability under environmental conditions	[104]
Recycling and Sustainability	Recycled Steel Fibre Composite	Promoted waste utilization and sustainable composite development	[98]
LCA	PLA/PHA Bio-Based Polymer System	Evaluated environmental impact and sustainability through LCA analysis	[102]
Green Synthesis and LCA	Waste-Derived GR Production	Demonstrated environmentally sustainable GR production routes	[105]

9 Applications of Carbon-Based Polymer Composites

9.1 Aerospace Applications

CBPCs are widely applied in aerospace construction owing to their lightweight and corrosion resistance, along with the ability to resist fatigue. Composite structures made of carbon fibres reinforced with polymers are popular for use in the fuselage, wing, tail structure, and internal components of an aircraft. These composite structures have several advantages over the traditional metallic structures since they can achieve a reduction of up to 20–50% of the total weight of such components.

9.2 Automotive Applications

CBPCs are utilized in automotive applications such as body panels of electric vehicles, battery housing units, chassis, and crash-resistant structures. The use of carbon fibre and graphene in automotive composites ensures that the vehicles remain light yet mechanically strong and safe. Lighter composite structures increase the energy efficiency and driving range of electric vehicles. Furthermore, composite battery cases increase impact resistance and thermal stability of electric vehicles. Red mud was found to be a suitable substitute for copper in resin matrix brake composites with enhanced hardness, impact strength, and high-temperature friction characteristics [106].

9.3 Construction Applications

Polymer composites consisting of carbon are currently being widely used in civil engineering construction projects for strengthening, repairing, and rehabilitation purposes. They are used in various infrastructure constructions, such as bridges and buildings, to increase load-bearing capability and durability. Self-healing composite systems offer increased durability by preventing cracks from forming and thus decreasing maintenance needs. Due to their corrosion-resistant properties, they are useful in tough environments.

9.4 Electronics Applications

CBPCs are highly conductive electrically and have been widely applied in flexible electronics, conductive coatings, wearable sensors, and smart electronics. The electric conductivity of the CNT-based and graphene-based composites can be in the range between 10^{-2} and 10^{4} S/m based on the type of filler and its content in the composite material. In addition to their use in electronic applications, CBPCs find applications in the development of EMI shielding materials, flexible electronics, energy storage, and sensing devices.

9.5 Biomedical Applications

CBPCs have been the subject of intense research in the field of biomedical engineering because of their high level of biocompatibility, mechanical stability, and functionality. These CBPCs find application in diverse biomedical applications such as drug delivery systems, tissue engineering systems, biosensors, etc. Composites of graphene and CNTs can be effective for promoting cell growth in tissue regeneration applications. Toxicity issues in some carbon-based materials still pose a challenge that must be addressed.

10 Challenges and Research Gaps

- Uniform distribution of carbon nanofillers in the polymer matrix is one of the biggest problems. Poor distribution results in agglomeration of fillers, thus affecting their efficiency as reinforcing materials. Advanced technologies should be used to attain a homogeneous distribution of the fillers.
- The performance of carbon-polymer composite materials is highly dependent on how the filler interacts with the polymer matrix. Poor bonding at the interface reduces the efficiency of stress transfer within the material, hence limiting its mechanical performance. Surface modification becomes necessary in such instances.
- Manufacturing high-grade carbon-based nanomaterials like CNTs and GR requires very costly manufacturing processes, which contribute to making the entire process of composite manufacture more expensive. It is necessary to develop cost-efficient manufacturing processes to ensure industrial viability.
- Many laboratory-scale processes for fabricating materials cannot be easily scaled up to a production-level scale. Achieving consistency in quality and performance throughout the production process is hard. Thus, there is a need for efficient processing methods.
- The recycling process of carbon-filled polymer matrix composites is quite challenging due to the strong bond between the filler and the polymer matrix. In addition, the lack of recycling facilities and expensive processing techniques has posed a problem in the commercialization of such composites.

11 Future Directions

- Future studies are anticipated to revolve around the production of sustainable carbon nanomaterials using renewable resources and industrial waste. The produced materials would be environmentally friendly, along with having good composite properties. The approach adopted would be an example of developing sustainable composite technology.

- The use of various CBRs together may result in the development of hybrid composites, which have better multifunctional properties. Multifunctionality is achieved due to improvements in the material's mechanical, thermal, and electrical properties all at once.
- Green fabrication processes have become very important for composite manufacturing. Such green fabrication processes not only help in saving energy but also in reducing toxic chemicals as well as waste material used during the manufacturing process.
- Composites of the future have various functions incorporated into one system, like strength, heat transfer capability, electrical conductivity, and sensing capability. This enhances their efficiency, as well as reduces the need for different components. These kinds of composites would be ideal for aerospace, automotive, and electronics applications.
- The design of smart materials that can sense, monitor, and adapt is an emerging field of study. Such materials able to sense damage and monitor themselves, adapting as per their environment. The use of such smart materials improves the safety, reliability, and efficiency of structures.

12 Conclusion

The review has systematically analyzed recent progress in the field of CBPCs and showcased the major impact made by carbon-based fillers on improving the performance of composites. It has been observed that carbon fibres are the best type of filler used for making composites strong and reliable, while CNTs and graphene-based filler materials have proved themselves to be great at thermal and electrical conduction and multifunctionality. Biochar composites can also be termed sustainable and affordable options for developing composites. On the other hand, some advanced fabrication methods like compression moulding, RTM, electrospinning, additive manufacturing, and *in-situ* polymerization have been found to greatly improve the performance of composites.

The comparative analysis showed that using CNTs and graphene in composite materials is the best solution for achieving optimal performance, whereas carbon fibre-based composite materials are still recommended in cases requiring strength and stiffness. Although significant advancements have been made in recent years, the issues connected to the distribution of nanofillers within the matrix, compatibility between the interface, cost of production, scalability, and recyclability have prevented their mass adoption. In general, the reviewed literature confirms that CBPCs are materials with great promise for applications in the aerospace, automotive, construction, electronics, energy storage, and biomedicine sectors due to their low weight and multifunctional nature. The reviewed studies suggest that the suitability of CBPCs depends on the combined influence of reinforcement type, processing method, mechanical characteristics, functionality, cost, and sustainability. Carbon fibres are particularly suitable for structural applications requiring high strength and stiffness, whereas CNTs and graphene are advantageous for multifunctional and conductive applications. Overall, the analysis indicates that future CBPC development should focus on balancing performance with cost, scalability, recyclability, and environmental sustainability to support wider industrial adoption.

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