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Carbon black-reinforced polymer composites: multifunctional advancements, characterization, and industrial applications

ABSTRACT

Carbon black (CB) has emerged as a transformative additive in polymer matrix composites (PMCs), offering unparalleled enhancements in mechanical, electrical, and thermal properties. This comprehensive review synthesizes recent advancements in CB-reinforced composites, focusing on their multifunctional roles in aerospace, automotive, electronics, and energy applications. Key findings highlight CB's ability to achieve electrical percolation at ultralow loadings (0.58 wt%), improve tensile strength by 15–40%, and enable electromagnetic interference (EMI) shielding exceeding 150 dB in hybrid systems with carbon nanotubes (CNTs) or graphene.

The review systematically examines CB's reinforcement mechanisms, including its fractal aggregate structure, interfacial adhesion, and synergistic effects in hybrid composites. Critical applications such as lightweight EMI shielding, UV-resistant coatings, and conductive adhesives are discussed, alongside industrial challenges like dispersion uniformity and long-term durability. Emerging trends in sustainable alternatives (e.g., bio-derived CB, recycled CB from tires) and advanced manufacturing (e.g., 3D printing) are highlighted as pathways to address environmental concerns and scalability limitations.

Despite its versatility, challenges persist in optimizing CB-polymer interfaces, mitigating health risks, and standardizing processing techniques. Future research directions emphasize AI-driven material design, surface functionalization, and circular economy approaches to unlock CB's full potential in next-generation smart composites. This review underscores CB's pivotal role in advancing high-performance materials while calling for interdisciplinary collaboration to bridge laboratory innovations with industrial adoption.

Keywords*: Carbon black, polymer composites, EMI shielding, hybrid nanocomposites, electrical conductivity, sustainable materials.*

1. INTRODUCTION

The growing demand for advanced materials with superior mechanical, thermal, and functional properties has driven significant innovations in polymer matrix composites (PMCs). These materials, engineered by embedding reinforcing fibers within a polymer resin matrix, offer exceptional strength-to-weight ratios, corrosion resistance, and design flexibility, making them indispensable in aerospace, automotive, civil infrastructure, and sports equipment [1,2].

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Among polymer matrices, epoxy resins are particularly favored due to their low viscosity, excellent adhesion, and minimal shrinkage during curing, making them ideal for high-performance composite systems [3-5]. Fiber-reinforced polymer composites (FRPCs), incorporating high-strength fibers such as glass, carbon, or aramid, have seen rapid adoption in industries requiring lightweight yet durable materials [6].

Beyond structural performance, the need for multifunctional composites—capable of integrating electrical conductivity, thermal stability, and environmental resistance—has spurred research into nanofiller-enhanced polymer systems[7][8][9]. Conductive polymer nanocomposites (PNCs) incorporating nanocarbon additives such as carbon black (CB), graphene nanoparticles (GNPs), and carbon nanotubes (CNTs) have demonstrated significant potential in applications ranging from flexible electronics to electromagnetic interference (EMI) shielding and energy storage[10-13].Among these nanofillers, carbon black stands out due to its commercial availability, cost-effectiveness, and multifunctional contributions [14]. As a fine particulate form of carbon, CB is well-known for its electrical conductivity (10^{-2} to 10^{2} S/cm), UV resistance, and mechanical reinforcement [15,16]. Studies have shown that CB nanoparticles can significantly enhance polymer systems, such as ethylene-co-butyl acrylate (EBA), through conductive network formation described by percolation theory, typically at volume fractions around 8% [17,18].

Despite these advancements, critical research gaps remain. While property-specific enhancements (e.g., conductivity, mechanical reinforcement) have been explored, comprehensive assessments of long-term durability, mechanical performance under operational stresses, and processing challenges (e.g., dispersion uniformity) are still lacking [19,20]. Addressing these gaps is crucial for advancing the scalability and real-world applicability of CB-reinforced FRP composites.

This review provides a systematic analysis of recent research on carbon black-enhanced FRP composites, focusing on their influence on mechanical properties, thermal stability, electrical conductivity, and environmental resistance. By consolidating findings from diverse studies, we elucidate the underlying mechanisms of CB's reinforcing effects and assessits practical implications for industrial applications.

2. BACKGROUNDOF CARBON BLACK

2.1. Origin of Carbon Black

Carbon black (CB) is a fine black powder composed almost entirely of elemental carbon. Commercially available for over a century, it is a critical industrial material, primarily used as a reinforcing agent in vehicle tires and automotive rubber products. Additionally, it is incorporated into inks, paints, coatings, and plastics due to its pigmenting and conductive properties. Carbon black is typically produced through partial combustion or thermal decomposition of hydrocarbons under controlled conditions, yielding different grades with tailored properties such as surface area, particle size, structure, conductivity, and color [21].

Although often confused with soot, carbon black is a manufactured product with controlled morphology and composition. In contrast, soot is a byproduct of incomplete combustion, comprising a heterogeneous mix of carbonaceous materials, higher organic fractions, and varying ash content [22]. Structurally, carbon black forms grape-like acini form aggregates of fused spherical primary particles, which further agglomerate into larger clusters as shown in Figure 1. Carbon black types include furnace black, thermal black, lamp black, channel black, and acetylene black—each differing in production method and particle properties [23]. Two key metrics define its structure: Primary Particle Size: The mean diameter of individual spherical particles. It is typically inversely proportional to the surface area. Aggregate Size: The extent of the fused chain of primary particles, forming the rigid internal structure and it is shown in Figure 2.

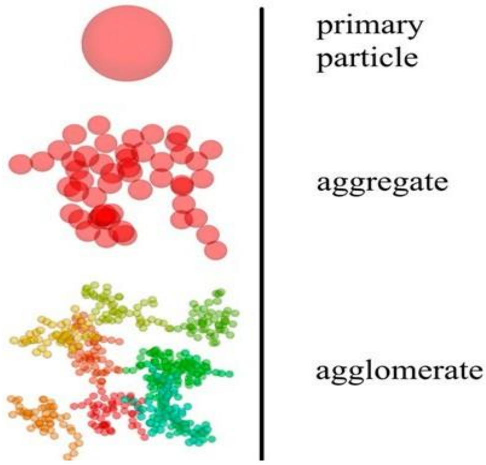

Figure 1. Structural levels of carbon black aggregates [19]

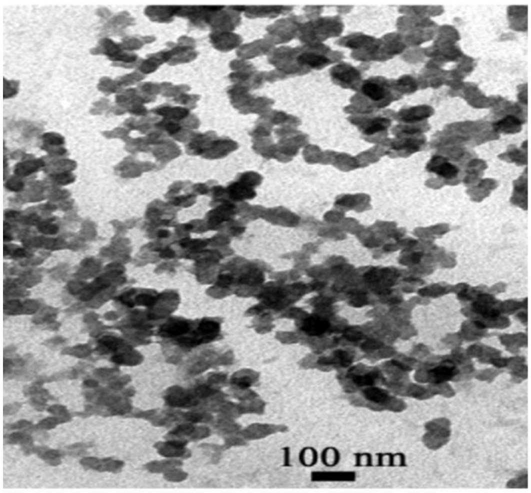

Figure 2: TEM micrograph of a branched carbon black aggregate [19]

An additional critical property is structure, referring to the void volume within aggregates. It affects the material's ability to absorb oil and contributes to reinforcement and dispersion behavior. This is typically measured using the dibutyl phthalate (DBP) absorption test, expressed in mL per 100 g of carbon black [24]. Historically, industry designations such as High-Abrasion Furnace (HAF) or Semi-Reinforcing Furnace (SRF) black were used. These have largely been replaced by the ASTM classification system, introduced in 1966, particularly for rubber-grade carbon blacks. The system uses the format Nxyz, where: N indicates normal cure behavior in rubber; x denotes a group number based on average particle size; and yz are arbitrary identifiers within the group and it is shown in Table 1.

Table 1. ASTM classification for rubber-grade carbon blacks [24]

Grade	Group (x)	Particle Size Range (nm)	Surface Area (m^2/g)
N110	1	11–19	121–150
N220	2	20–25	100–120
N330	3	26–30	70–99
N550	5	40–48	40–49
N660	6	49–60	33–39
N772	7	61–100	21–32
N990	9	201–500	0–10
N110	1	11–19	121–150
~~N220~~	~~2~~	~~20–25~~	~~100–120~~

Carbon black is also used in conductive polymer composites (CPCs) for EMI shielding. High loading levels enhance conductivity but may degrade mechanical performance and complicate processing. Studies show that CB dispersed in polymer blends like PP, PC, PS, and PLA can form conductive networks with enhanced shielding effectiveness. For instance, a microporous PLA foam with 8 vol% CB exhibited over 150 dB shielding across the 100 Hz–100 kHz range.

2.2 Production of Carbon Black

Carbon black is a fine particulate form of elemental carbon produced industrially through several distinct processes, each yielding products with unique physicochemical properties. The five principal production methods - furnace black, thermal black, channel black, lamp black, and acetylene black processes - are selected based on desired particle characteristics (size, surface area, structure, purity) for specific applications ranging from rubber reinforcement to conductive materials [25].

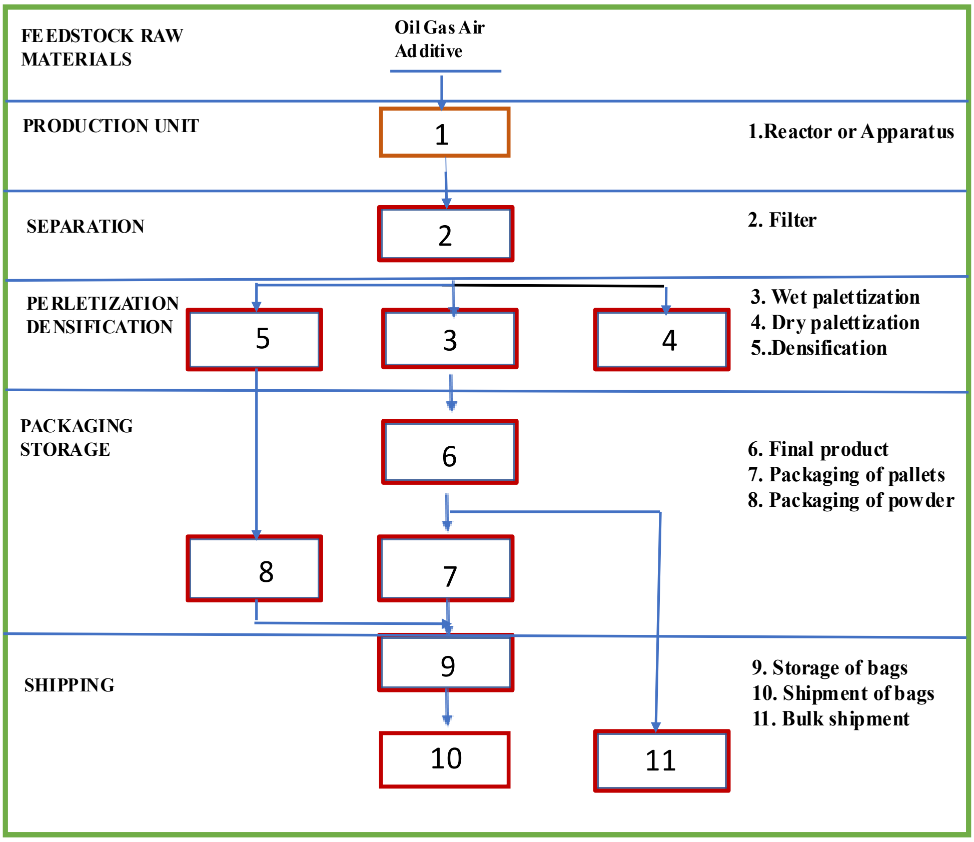

Figure 3. Schematic diagram of the individual process steps in a carbon black production unit [92]

The production process, illustrated in Figure 3, begins in the carbon black production unit (1), where reactors generate an aerosol mixture of process gas and carbon black. This mixture undergoes cooling before entering collection systems (2) for solid-gas separation. The resulting "fluffy black" (characterized by low bulk density) is then densified into either powder black or pelletized black (5). Wet (3) or dry (4) pelletization methods may be employed, with final products packaged accordingly (6 -7): powder black in bags (8), and pelletized black in bags, shrink-wrapped pallets (9-10), or bulk containers (11) for transport.

2.3. Comparative Analysis of Production Methods

The method of the production of carbon black is described below:

- **Furnace Black Process:** The dominant commercial method (1320-1540°C) produces particles (10-500 nm) with tunable structure and moderate-high surface area, ideal for rubber reinforcement and conductive composites [18].
- **Channel Black:** Historically important for pigments/inks [19], this method yields fine particles (10-30 nm) with excellent dispersibility but has been largely phased out.
- **Thermal Black:** Methane decomposition (1200-1400°C) creates large particles (200-500 nm) suited for insulation [18].
- **Lamp Black:** Remains relevant for specialty ink production [20].
- **Acetylene Black:** Produces chain-like aggregates (30-50 nm) with exceptional conductivity (60-70 m²/g), crucial for energy storage applications [21].

The methods utilized for the production are compared in Table 2, which provides a detailed comparison of the five industrial production methods. The furnace method dominates commercial production due to its versatility, while acetylene black serves specialized conductive applications. Future developments should focus on improving sustainability without compromising these performance characteristics.

Table 2. Overview of Industrial Carbon Black Production Methods, Typical Properties, and Applications

Production Method	Feedstock	Process Type	Temp (°C)	Particle Size (nm)	Structure	Surface Area (m²/g)	Key Features	Typical Applications	Author(s)
Furnace Black	Heavy aromatics (e.g., coal tar, ethylene cracking tar)	Continuous, oxygen-limited pyrolysis	1320–1540	10–500	Tunable (low–high)	Moderate to high	High yield, scalable, adjustable morphology and purity	Rubber reinforcement, conductive composites	C. Dwivedi et al.[94]
Channel Black	Natural gas or vaporized crude oil	Continuous, surface deposition	~1300–1500	10–30	High surface oxidation	High	Fine particles with high dispersibility; historically significant; now largely obsolete	Pigments, inks, coatings	J. A. Bakken et al.[95]
Thermal Black	Natural gas (methane)	Cyclic, non-oxidative decomposition	1200–1400	200–500	Low aggregation	Low	High purity; low surface activity; large particles; batch-based	Insulation, low-conductivity fillers	C. Dwivedi et al.[94]
Lamp Black	Liquid hydrocarbons (vegetable or mineral oil)	Batch, incomplete combustion	~900–1200	50–100	Low to moderate	Moderate	Oldest method; low yield; relatively high volatile content	Specialty inks and historical coatings	N. Kokel[96]
Acetylene Black	Acetylene gas (C_2H_2)	Self-sustained exothermic decomposition	800–1200	30–50	Chain-like aggregates	High (60–70)	Exceptional conductivity and purity; niche industrial use	Batteries, fuel cells, conductive polymers	C. Siderius[97]

2.4. Characterization and Testing Methods of Carbon Black

The performance of carbon black (CB) in composite materials is governed by three fundamental characteristics: morphology, surface chemistry, and dispersion state. A systematic understanding of these properties through advanced characterization techniques is essential for optimizing CB's functionality in various applications. This section provides a comprehensive overview of state-of-the-art characterization methods, organized by their specific analytical capabilities.

2.4.1. Morphological Characterization

The morphological properties of CB, including particle size, aggregate structure, and surface area, are most commonly evaluated using gas adsorption and liquid absorption techniques. The Brunauer-Emmett-Teller (BET) surface area measurement (ASTM D6556) serves as a primary indicator of particle size, with nitrogen adsorption isotherms providing quantitative data on specific surface area [26]. This parameter inversely correlates with primary particle diameter, where higher surface areas (typically 20-1500 m^2/g) indicate smaller particles and greater reinforcement potential. Complementing this, the dibutyl phthalate (DBP) absorption test (ASTM D2414) quantitatively assesses aggregate structure by measuring the void volume between complex CB aggregates [27]. High DBP values (80-200 mL/100g) reflect highly branched, open structures that enhance reinforcement in tire tread formulations.

Advanced microscopy techniques provide direct visualization of CB nanostructure. Transmission electron microscopy (TEM) offers unparalleled resolution (≤1 nm) for examining primary particle size distribution (typically 10-500 nm), aggregate shape, and the degree of particle fusion [28]. Scanning electron microscopy (SEM) proves particularly valuable for studying CB dispersion in composite matrices at the micron scale, revealing agglomeration states and interfacial interactions [29]. Modern automated image analysis systems now enable quantitative characterization of aggregate parameters from these microscopic techniques.

2.4.2. Structural and Chemical Analysis

Structural and chemical characterization employs powerful spectroscopic and diffraction methods. X-ray diffraction (XRD) patterns reveal the crystalline structure of CB, particularly the interplanar spacing (d002) between graphitic layers (typically 3.35-3.60 Å) and crystallite dimensions (Lc and La) [30]. Raman spectroscopy provides complementary information through the D and G band intensity ratio (ID/IG), which quantifies structural disorder and the degree of graphitization [31]. These techniques collectively characterize the atomic-scale structure that influences CB's electrical and thermal properties.

Recent studies have expanded characterization protocols for recovered carbon black (rCB) to evaluate its potential as a sustainable alternative to virgin CB. Comprehensive analyses including elemental and proximate analyses, X-ray fluorescence (XRF) for ash composition, and Fourier Transform Infrared (FTIR) spectroscopy have been employed to assess the quality of demineralized rCB[32,33]. Such characterization is particularly important given the growing interest in pyrolysis-derived carbon black from waste tires as an environmentally friendly material source [31].

2.4.3. Functional Performance Evaluation

Functional performance testing evaluates CB in practical applications through several key methods:

1. Electrical conductivity measurements: Performed on compressed pellets or polymer composites to determine the percolation threshold and volume resistivity (typically 10-1-1010 Ω·cm) [34]. These measurements are crucial for conductive applications such as antistatic packaging or battery electrodes.
2. Dispersion quality assessment: Combines microscopic examination with rheological analysis, where changes in melt viscosity and storage modulus (G') indicate the state of CB distribution in polymer matrices.
3. Advanced nanoscale analysis: Techniques like atomic force microscopy (AFM) and small-angle X-ray scattering (SAXS) are increasingly employed for detailed dispersion analysis in high-performance composites [34].

The integration of these characterization methods provides a complete picture of CB properties, from primary particle morphology to bulk composite performance. This multi-scale approach enables manufacturers to tailor CB characteristics for specific applications ranging from tire reinforcement to advanced conductive materials.

2.4.4. Emerging Trends and Future Directions

Recent advances in characterization technology continue to enhance our understanding of structure-property relationships in carbon black systems. Notable developments include:

- The application of machine learning algorithms to predict composite performance based on characterization data
- In-situ characterization techniques for real-time monitoring of CB dispersion during processing
- High-throughput screening methods for rapid evaluation of CB grades and formulations

These innovations are particularly valuable for the development of sustainable CB alternatives and hybrid composite systems, where precise characterization of complex interactions between multiple filler types is essential.

The comprehensive characterization of CB remains critical for both fundamental research and industrial applications, enabling the optimization of composite materials for an increasingly diverse range of technological applications. Ongoing developments in analytical techniques promise to further enhance our ability to understand and control CB's performance in polymer composites.

Table 3.: The characterization methods, their purposes, key parameters measured, and applications:

Characterization Method	Purpose	Key Parameters Measured	Applications	References
BET Surface Area Analysis	Determine particle size and specific surface area	Surface area (m²/g), pore volume	Rubber reinforcement, conductive composites	[26], .
DBP Absorption Test	Assess aggregate structure and branching	Void volume (mL/100g), structure level	Tire tread formulations, elastomer composites	[27]
TEM/SEM	Visualize particle morphology and dispersion	Primary particle size (10–500 nm), aggregate shape	Quality control, dispersion optimization	[28], [29]
XRD	Analyze crystallinity and interlayer spacing	d-spacing (Å), crystallite size (Lc, La)	Conductive composites, thermal stability studies	[30]
Raman Spectroscopy	Evaluate graphitization and structural defects	ID/IG ratio, disorder quantification	High-performance composites, EMI shielding	[31]
XRF/FTIR	Determine elemental composition and functional groups (for rCB)	Ash content, surface chemistry	Recycled CB quality assessment, sustainability studies	[32][33].
Electrical Conductivity Test	Measure percolation threshold and resistivity	Volume resistivity (Ω·cm), percolation threshold	Antistatic materials, battery electrodes, EMI shielding	[34]
Rheological Analysis	Assess dispersion quality in polymer matrices	Melt viscosity, storage modulus (G')	Process optimization, filler-matrix interaction studies	[34]
AFM/SAXS	Nanoscale dispersion and interface analysis	Agglomeration size, filler distribution	High-performance nanocomposites, hybrid filler systems	[34]

Table 3. provides a comprehensive overview of the key techniques used to characterize carbon black (CB), each serving distinct yet complementary purposes in understanding its properties and applications. BET surface area analysis and DBP absorption tests form the foundation for assessing CB's physical attributes, with BET quantifying specific surface area and porosity—critical for rubber reinforcement and conductive composites—while DBP evaluates aggregate structure, which directly influences elastomer performance. Advanced imaging techniques like TEM and SEM offer visual insights into particle morphology and dispersion, essential for quality control and optimizing composite formulations. XRD and Raman spectroscopy probe the material's crystallinity and defect structures, providing valuable data for applications requiring precise electrical or thermal properties. Chemical characterization methods such as XRF and FTIR are indispensable for analyzing surface chemistry, particularly in recycled CB, where ash content and functional groups determine suitability for sustainable applications. Electrical conductivity tests and rheological analyses bridge the gap between fundamental properties and practical performance, measuring percolation behavior and polymer-filler interactions, respectively. Finally, high-resolution techniques like AFM and SAXS enable nanoscale investigation of dispersion and interface dynamics, crucial for developing advanced nanocomposites. Together, these methods create a robust framework for tailoring CB properties to specific industrial needs, from tire manufacturing to energy storage and EMI shielding, while supporting the growing emphasis on sustainable material development.

2.5. Carbon Black-Based Composites for Electromagnetic Interference (EMI) Shielding: Mechanisms, Performance, and Applications

2.5.1. The Growing Importance of CB in EMI Shielding

The escalating demand for electromagnetic interference (EMI) shielding solutions has become paramount in contemporary electronic systems, telecommunications infrastructure, and aerospace technologies, where sensitive equipment requires robust protection against disruptive electromagnetic radiation [35]. While conventional metal-based shielding materials (e.g., copper, aluminum) demonstrate excellent shielding effectiveness, their inherent limitations including excessive weight, susceptibility to corrosion, and challenging processing requirements have stimulated significant research into alternative solutions. Conductive polymer composites (CPCs) incorporating carbon-based fillers have emerged as particularly promising candidates, with carbon black (CB) standing out due to its unique combination of advantages: exceptional cost-effectiveness, superior process ability with various polymer matrices, and the ability to precisely tune electrical properties through controlled dispersion and loading [36]. The versatility of CB-based shielding materials enables their application across diverse sectors, from consumer electronics to military-grade shielding requirements.

2.5.2 Mechanisms of EMI Shielding in CB-Polymer Composites

CB-polymer composites attenuate electromagnetic radiation through three fundamental mechanisms working in concert:

- Absorption Dominated Shielding: The conductive CB network facilitates multiple internal reflections and subsequent dissipation of electromagnetic energy as Joule heat through dielectric and conduction losses [37]. This mechanism becomes particularly significant when the composite possesses appropriate impedance matching with free space and sufficient dielectric loss characteristics.
- Reflection-Based Shielding: The conductivity mismatch between the composite surface and free space causes immediate reflection of incident radiation [38]. CB's high electrical conductivity (achievable at proper loading levels) enhances this reflection mechanism, especially at the air-material interface.
- Multiple Internal Reflections: The three-dimensional conductive network within the composite promotes successive scattering and attenuation of electromagnetic waves through repeated reflection pathways.

A critical performance parameter is the percolation threshold - the minimum CB concentration required to establish continuous conductive pathways through the polymer matrix. Recent studies demonstrate that optimized CB dispersion techniques, including surface modification and advanced mixing protocols, can significantly reduce this threshold (often to 2-5 wt%), thereby enhancing shielding effectiveness (SE) while maintaining favorable mechanical properties [39]. The SE performance follows a characteristic sigmoidal relationship with CB loading, exhibiting dramatic improvement once the percolation threshold is surpassed.

2.5.3. Key Performance Findings and Benchmarking of CB-Based EMI Shielding Materials

Recent advancements in carbon black (CB)-based electromagnetic interference (EMI) shielding materials have demonstrated remarkable progress in efficiency, multi-functionality, and structural design. Key developments include:

Performance Breakthroughs

- **High-Efficiency Shielding:** Composite systems now achieve >40 dB shielding effectiveness (SE) in the X-band (8–12 GHz) at moderate CB loadings (15–20 wt%), rivaling metal shields while reducing weight by 40–60% [40].
- **Hybrid Filler Synergy:** Combining CB with carbon nanotubes (CNTs) or graphene lowers percolation thresholds (<1.5 wt%) and enhances conductive networks through synergistic effects [40].
- **Multifunctional Integration:** Modern composites combine EMI shielding with thermal conductivity (up to 2.5 W/mK), mechanical reinforcement (300% strength improvement), and strain-sensing capabilities [41]. Frequency-Selective Designs: Advanced architectures enable targeted interference blocking while maintaining signal transparency in desired frequency bands [15].

Recent studies demonstrate significant advancements in carbon black (CB)-based composites for electromagnetic interference (EMI) shielding, as summarized in Table 4. Polylactic acid (PLA)/CB foams with a microcellular structure (85% porosity) achieve exceptional shielding effectiveness (SE) of 150 dB in the low-frequency range (100 Hz–100 kHz), leveraging porous architectures for enhanced wave attenuation [42]. In contrast, polypropylene (PP)/CB composites with silane-modified surfaces provide moderate SE (45 dB) in the X-band (8–12 GHz), offering a balance between performance and process ability for commercial applications [43]. Hybrid systems exhibit further improvements: a 3D segregated network of CB/carbon nanotubes (CNTs) attains 62 dB SE at a low filler loading (3.2 vol%) in the Ku-band (12–18 GHz) [44], while a CB/graphene/ethylene-propylene-diene monomer (EPDM) composite achieves remarkable SE (89 dB) in the X-band through binary filler synergy [45]. These results underscore the critical role of material design—including porosity, surface modification, and hybrid filler integration—in tailoring CB composites for specific frequency ranges and performance requirements. The data highlight CB’s versatility as a conductive filler, particularly when combined with Nano carbons (CNTs, graphene) to optimize conductivity and SE at reduced filler loadings.

Table 4. Comparative Performance of Carbon Black-Based EMI Shielding Composites

System	Key Innovation	SE Performance	Frequency Range	Author(s)
PLA/CB foams	Microcellular structure (85% porosity)	150 dB	100 Hz–100 kHz	S. K. Ghosh *et al*[15]
PP/CB composites	Silane-modified CB surfaces	45 dB	X-band (8–12 GHz)	[89]
Hybrid CB/CNT systems	3D segregated network architecture	62 dB (3.2 vol%)	Ku-band (12–18 GHz)	S. O. Oruma and S. Petrovic[42]
CB/graphene/EPDM	Binary filler synergy	89 dB	X-band	D. Ponnamma and M. A. A. Al-Maadeed [40]

Hybrid systems incorporating CB with 2D (graphene, MXenes) or 1D (CNTs) materials exhibit exceptional performance, leveraging complementary charge transport mechanisms. CB particles act as conductive bridges between high-aspect-ratio fillers, reducing percolation thresholds by up to 60% compared to single-filler systems [44]. These innovations position CB composites as lightweight, multifunctional alternatives to conventional EMI shields, with ongoing research focusing on novel architectures, advanced processing, and surface modifications for further optimization.

2.5.4. Emerging applications and future perspectives

Carbon black (CB)-based EMI shielding materials are increasingly being adopted across cutting-edge industries due to their lightweight, process ability, and multifunctional capabilities. In 5G infrastructure, CB composites (1.1–1.4 g/cm³) are being developed as radome materials for mmWave base stations (28/39 GHz), balancing high shielding effectiveness with controlled wave transparency to ensure signal integrity [45]. The electric vehicle (EV) sector leverages CB-polymer composites for integrated shielding in battery management systems (DC–100 kHz) and power electronics (10–100 MHz), where they simultaneously provide EMI protection and thermal management (λ = 0.8–1.2 W/mK) [46]. Additionally, flexible electronics benefit from stretchable CB composites (ε > 150%) that maintain SE > 30 dB even after 1000 bending cycles, making them ideal for wearable medical devices and foldable displays [47]. Future research is focused on developing multifunctional composites that integrate EMI shielding with enhanced thermal conductivity (>2 W/mK) and mechanical strength (>50 MPa), as well as smart shielding materials with frequency-selective or dynamically tunable responses. Sustainability is another key direction, with efforts underway to incorporate bio-based polymers and recycled CB to reduce environmental impact. Advances in nano-structuring, hybrid filler systems, and advanced manufacturing techniques (e.g., 3D printing) are expected to further optimize CB dispersion and composite performance, unlocking new applications in next-generation electronics, aerospace, and automotive industries [47]

2.6. Critical Factors Influencing EMI Shielding Effectiveness in CB Composites

The electromagnetic interference (EMI) shielding effectiveness (SE) of carbon black (CB)-polymer composites is governed by several interdependent factors, including filler characteristics, dispersion quality, and matrix properties.

- CB Type and Structural Properties The choice of CB variant—such as acetylene black versus furnace black—critically affects SE due to differences in microstructure and purity. Acetylene black, synthesized via acetylene decomposition, exhibits higher graphitization, porosity, and branched aggregates, which enhance conductivity and EMI shielding compared to furnace black with its lower purity and more disordered structure [48].
- Particle Morphology and Aggregation Shielding performance is sensitive to CB particle size, shape, and aggregation state. Smaller particles with high surface area and structured chain-like aggregates promote efficient percolation pathways, whereas large or irregular aggregates impede charge transport [49].
- Dispersion Uniformity in Polymer Matrices A homogeneous CB distribution is essential for establishing continuous conductive networks. Agglomeration introduces interfacial resistance, degrading SE. Advanced dispersion techniques (e.g., sonication, surfactant modification, and melt blending) mitigate this issue [50].
- Filler Loading and Percolation Dynamics SE escalates sharply upon reaching the percolation threshold, where conductive pathways first form. While higher CB loadings improve SE, excessive filler content can compromise mechanical flexibility and process ability [51].
- Polymer Matrix Selection The matrix's dielectric constant and viscosity significantly influence CB dispersion and polarization effects. High-

dielectric-constant polymers (e.g., polyaniline) enhance absorption loss, while low-viscosity thermoplastics (e.g., polypropylene) facilitate superior filler dispersion compared to viscous epoxies [52].

These elements collectively determine the formation of conductive networks and charge transport efficiency, as summarized in Table 5.

Table 5. Critical factors governing EMI shielding performance in CB composites

Factor	Influence on EMI SE	Author(s)
CB Type	Acetylene black outperforms furnace black due to superior conductivity and structure	Al-Saleh & Sundararaj [48]
Morphology	Smaller, structured aggregates optimize percolation pathways	Zhang et al. [49]
Dispersion	Uniform distribution minimizes agglomeration and interfacial resistance	Isari et al. [50]
Filler Loading	SE rises post-percolation; excessive loading degrades mechanical properties	Luo & Chung [51].
Matrix Properties	High dielectric constant enhances absorption; low viscosity improves dispersion	Wang et al. [52]

3. THE MULTIFUNCTIONAL ROLE OF CARBON BLACK IN POLYMER COMPOSITES

3.1. Fundamental Roles and Mechanisms

Carbon black (CB) is a versatile reinforcing filler in polymer composites, valued for its ability to simultaneously enhance electrical conductivity, mechanical properties, and thermal stability. Produced via incomplete hydrocarbon combustion, CB consists of nanostructured carbon particles with high surface area and tunable conductivity, making it indispensable for applications in electronics, automotive, and aerospace industries [53].

Electrical Conductivity and EMI Shielding CB's primary role lies in establishing conductive networks within polymer matrices, enabling applications such as antistatic coatings, sensors, and electromagnetic interference (EMI) shielding. The percolation threshold—the critical CB concentration required for conductivity—depends on particle size, dispersion quality, and polymer compatibility [54]. Recent advances in surface functionalization and dispersion techniques (e.g., surfactant-assisted mixing, in-situ polymerization) have further optimized electrical performance, achieving lower percolation thresholds and higher conductivity [55].

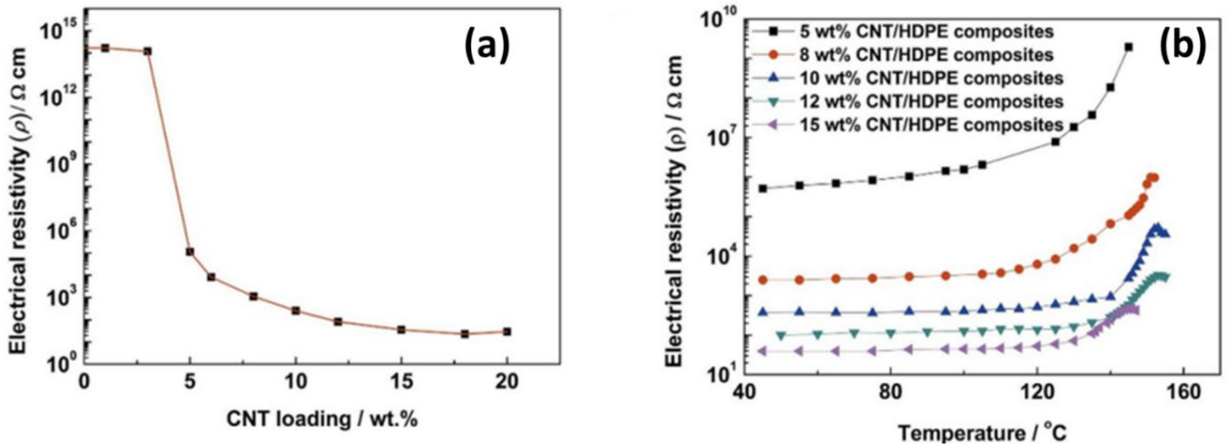

Figure 4. Electrical Resistivity of CNT/HDPE Composites: (a) vs. CNT Loadings, (b) vs. Temperature [57]

Mechanical Reinforcement Beyond conductivity, CB significantly improves mechanical properties. Its high aspect ratio and nanoscale dimensions enhance wear resistance, impact strength, and tensile properties, particularly in rubber composites for tires, seals, and industrial components [56]. The electrical properties of carbon nanotube (CNT)-reinforced polymers are governed by percolation dynamics and temperature-dependent conduction mechanisms. In a study by Zeng et al. [57], CNT/high-density polyethylene (HDPE) composites exhibited classic percolation behavior, with a critical threshold at 4.0 wt% CNT loading a shown in Figure 4a. Below this threshold, the material remained insulating, dominated by the HDPE matrix. Beyond 4.0 wt%, resistivity dropped sharply as CNTs formed interconnected conductive pathways.

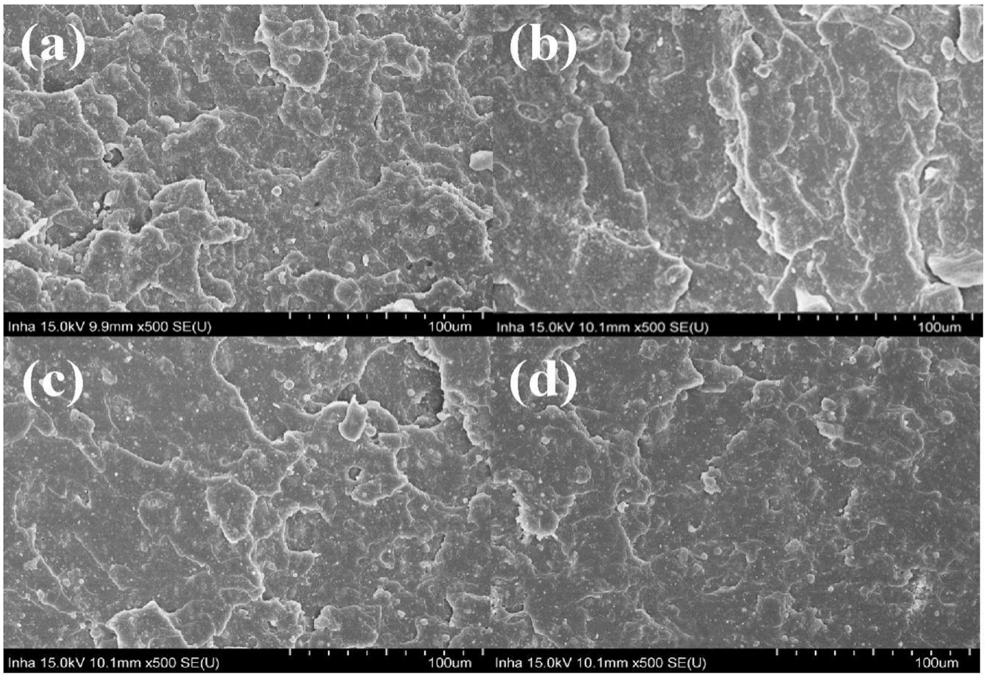

Figure 5. SEM photomicrographs of the tensile fracture surfaces of the composites: (a) N 220/NR, (b) N 330/NR, (c) N 550/NR and (d) N 774/NR [60]

In fiber-reinforced polymers (FRPs), CB acts as a secondary filler, improving fiber-matrix interfacial bonding. Studies report increases in stiffness (e.g., 20–30% in tensile modulus) and tensile strength, especially under dynamic loads in automotive and aerospace applications [58],[59]. Scanning electron microscopy (SEM) analyses confirm that high-surface-area CB (e.g., N220 type) strengthens interfacial adhesion via London dispersive forces, while uniform dispersion prevents agglomeration-induced weakening [60],[61]. Thermal and Environmental Stability CB enhances thermal stability by dissipating heat and inhibiting polymer oxidation, as demonstrated by Zeng et al. [57]. Its UV-absorbing properties also protect composites from photo degradation, extending service life in outdoor applications. Patel and Desai [14] highlighted CB's role in improving FRP thermal resistance, critical for high-temperature environments. However, the composites displayed a notable Positive Temperature Coefficient (PTC) effect and it is shown in Figure 4b, where resistivity surged at elevated temperatures due to thermal expansion of the HDPE matrix disrupting the CNT network. Intriguingly, PTC intensity diminished at higher CNT loadings (>7 wt%), suggesting that denser, entangled CNT networks mitigate matrix-driven conduction losses. This behavior highlights the trade-off between percolation efficiency and thermal stability in conductive polymer composites.

Despite the advantages of CNTs and graphene, such as high aspect ratio and intrinsic conductivity, their reinforcement efficacy is often limited by nano-filler aggregation, as noted by Liu et al. [62]. To address this, hybridization with carbon black (CB) has emerged as a promising strategy. CB particles can act as spacers, improving CNT dispersion while synergistically enhancing electrical and mechanical properties. Such hybrid systems represent a viable route toward next-generation multifunctional composites for applications ranging from flexible electronics to self-regulating heaters.

As demonstrated in Table 6 [60], the mechanical performance of carbon black (CB)-reinforced natural rubber composites varies significantly with CB grade selection. The N220 grade, characterized by its high surface area (110-120 m^2/g) and small primary particle size (20-25 nm) [66], yields superior tensile strength (14.96 MPa) and elongation (441%) compared to other grades. This enhancement stems from N220's ability to form stronger interfacial interactions with the rubber matrix and create more extensive filler networks [56],67]. The N330 grade shows comparable modulus values to N220 (~5.1 MPa) but reduced tensile strength, consistent with its intermediate surface area (70-90 m^2/g) [68]. Larger-particle CB grades (N550: 40-50 nm, N774: 70-100 nm) exhibit progressively lower mechanical properties, though N774 demonstrates an interesting retention of elongation capability (424%) despite its lower modulus, possibly due to reduced filler-filler interactions allowing greater chain mobility [69]. These findings align with the general structure-property relationships in rubber composites, where smaller CB particles provide greater reinforcement but may compromise processability [70]. The data underscore the importance of CB grade selection based on application requirements, with N220/N330 preferred for high-performance applications and N550/N774 offering balanced properties for cost-sensitive formulations [71].

The scanning electron microscopy (SEM) images of tensile fracture surfaces for natural rubber (NR) composites reinforced with different carbon black (CB) grades are shown in Figure 5(a)-(d) [60]. These micrographs reveal distinct failure mechanisms correlated with CB morphology and interfacial interactions:

- **N220/NR (Panel a):** It exhibits a rough, tortuous fracture surface with extensive matrix tearing and well-dispersed CB aggregates (20–50 nm). This morphology aligns with its superior tensile strength (14.96 MPa, Table 5) and suggests effective stress transfer via strong polymer-filler interactions. The high surface area of N220 (110–120 m²/g) promotes covalent bonding with NR chains, leading to energy dissipation through matrix deformation rather than interfacial debonding [57,66].
- **N330/NR (Panel b):** The moderate surface roughness with localized CB agglomerates (~100 nm). The partial pull-out of larger aggregates correlates with its 15% lower tensile strength compared to N220 (Table 5), indicative of weaker interfacial adhesion. This behavior reflects N330's intermediate surface area (70–90 m²/g) and structure [68].
- **N550/NR (Panel c):** It displays smooth regions with visible CB agglomerates (200–300 nm) and clean filler pull-out. The lack of matrix deformation explains its reduced elongation (348%, Table 5), as larger N550 particles (40–50 nm) limit interfacial contact area and facilitate crack propagation along weak filler-matrix boundaries [69].

N774/NR (Panel d): This features a mixed morphology with both smooth zones and isolated fibrous fractures. The occasional matrix tearing accounts for its retained elongation (424%, Table 6), likely due to N774's low structure (70–100 nm particles) allowing limited polymer chain mobility around aggregates [70].

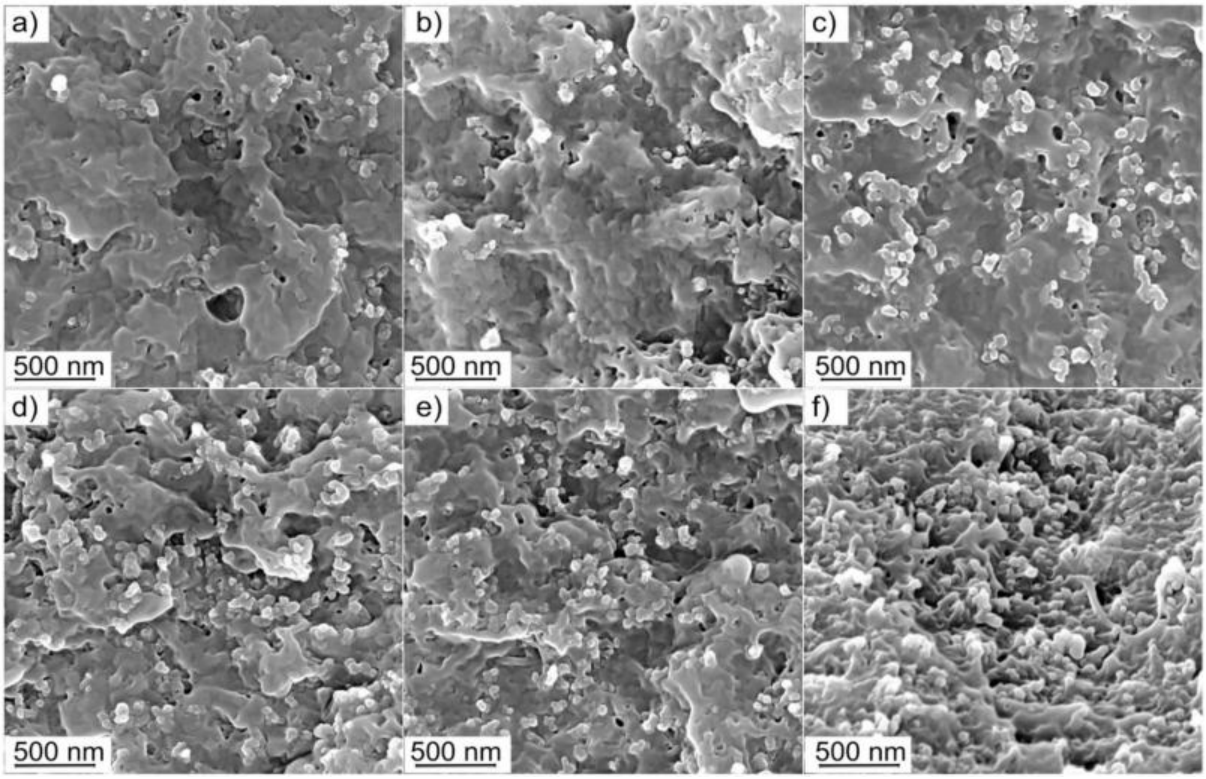

Figure 6. SEM images of CB-reinforced PA66 melt compounded composites with different filler content: 14 % (a), 16 (b), 17 (c); 18 (d); 21 (e) and 27 wt. % (f), respectively [63]

The SEM images in Figure 6 illustrate the morphological evolution of carbon black (CB)-reinforced PA66 composites with increasing filler content (14–27 wt%). At lower CB loadings (14–17 wt%), the particles are relatively well-dispersed, though minor aggregates are observed. As the CB concentration rises (18–27 wt%), the filler forms larger, interconnected agglomerates, indicating a percolation threshold where particle-particle interactions dominate. This transition suggests a trade-off between dispersion quality and the formation of conductive networks, which is critical for tailoring electrical and mechanical properties in such composites. The nanoscale morphology (evidenced by the 500 nm scale bar) aligns with typical CB structures, where primary particles cluster into larger aggregates at higher loadings. These findings highlight the importance of optimizing filler content to balance dispersion, conductivity, and mechanical performance in CB-reinforced polymer systems [63].

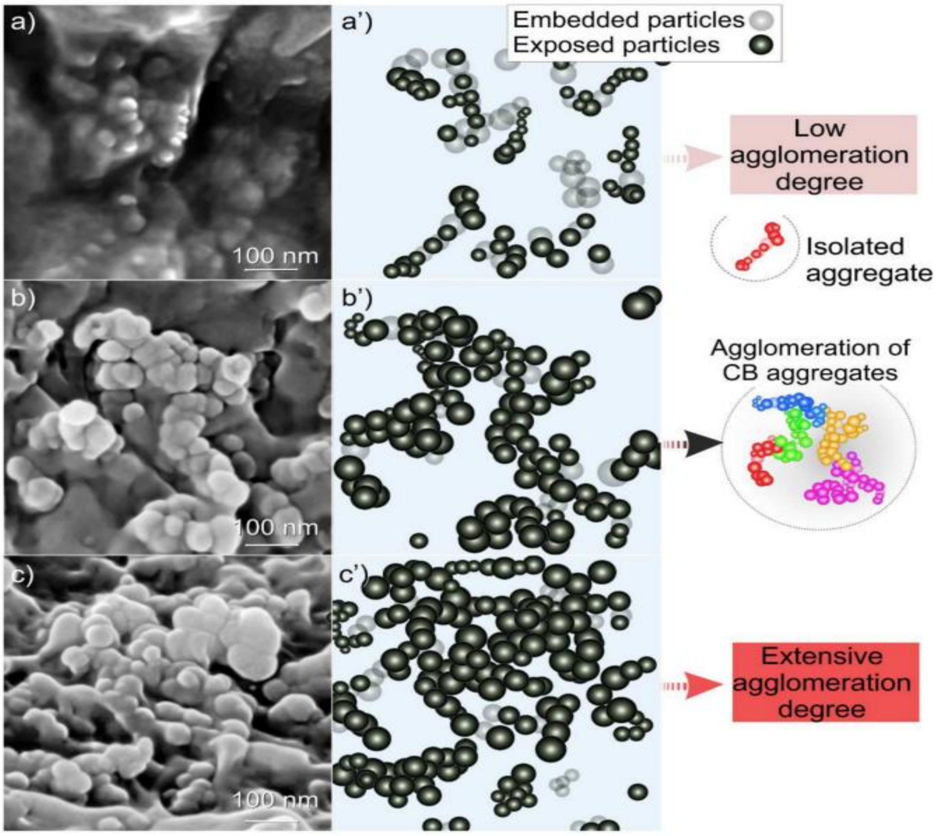

Figure 7. High-resolution FESEM images of CB-reinforced PA66 melt compounded composites with different filler content: 14 % (a), 17 (b), 21 wt. % (c), and the associated schematic representations illustrating the CB particles, their aggregates at the different filler loadings: 14 (a'), 17 (b'), 21 wt. % (c'); respectively [63]

The SEM in Figure 7 analysis reveals distinct morphological regimes of carbon black (CB) dispersion within the polymer matrix, characterized by progressive agglomeration with increasing filler loading. At low CB concentrations, isolated aggregates exhibit uniform distribution (low agglomeration degree) [23], with both embedded particles (integrated into the matrix) and exposed particles (surface-localized) observed, suggesting varied interfacial interactions. As filler content rises, intermediate agglomeration emerges, marked by interconnected CB clusters forming initial percolation pathways, where particle-particle interactions begin to outweigh particle-matrix adhesion. At high loadings, extensive agglomeration dominates, creating dense CB networks essential for electrical conductivity but potentially compromising mechanical properties due to reduced homogeneity. The nanoscale morphology (100–400 nm) confirms that these agglomerates consist of primary CB particles (typically 20–100 nm) clustered into larger structures. These findings highlight the critical trade-off in composite design: well-dispersed CB enhances mechanical performance through efficient stress transfer, while agglomerated networks enable electrical percolation at the expense of ductility. The coexistence of embedded and exposed particles further underscores variability in interfacial adhesion, which may influence composite durability. Collectively, these observations align with percolation theory and emphasize the need to optimize CB loading for target applications—balancing conductivity and structural integrity in conductive polymer nanocomposites [63].

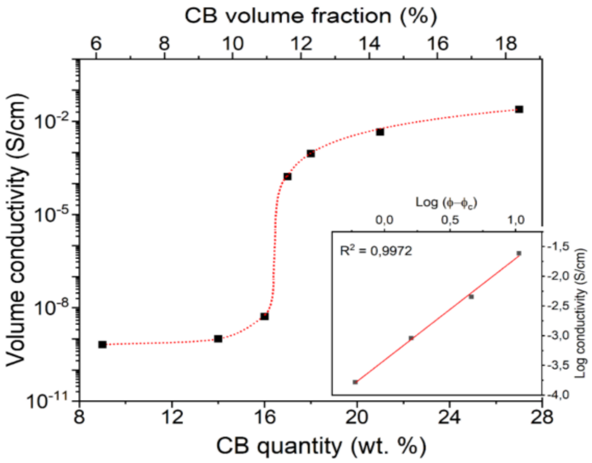

Figure 8. Room temperature electrical conductivity as a function of the CB loading in CB-filled melt-compounded PA composites. The log–log plot of conductivity at 25 ◦C is shown in the inset [63].

The electrical conductivity data of CB-filled PA composites (Figure 8) exhibits classic percolation behavior, with three distinct regimes evident in the log-log plot: (1) an insulating region at low CB loadings (<16 wt%), (2) a sharp transition zone (16-18 wt%) where conductivity increases by several orders of magnitude, marking the percolation threshold, and (3) a conductive plateau (>18 wt%) where additional CB yields minimal conductivity gains. The abrupt conductivity jump reflects the formation of continuous conductive pathways, while the subsequent plateau indicates network saturation. These quantitative results align perfectly with the SEM-observed morphological transition from isolated CB aggregates to interconnected networks, demonstrating that the percolation threshold corresponds to the critical CB concentration where particle agglomeration creates system-spanning conductive paths. The findings underscore the importance of precisely controlling CB content near the percolation threshold to achieve optimal electrical performance while maintaining mechanical properties in conductive polymer composites [63].

3.2. Utilizing Carbon Black in Composites for Industrial Applications

Carbon black (CB) is a versatile material with a broad spectrum of industrial applications, ranging from small-scale uses to large-scale critical infrastructure. Its multifunctional properties—including pigmentation, conductivity enhancement, viscosity modification, static charge dissipation, and UV protection—make it indispensable across numerous sectors [64]. While CB's primary application remains in rubber reinforcement (e.g., tires, hoses, belts, gaskets, and molded automotive components), its utility extends far beyond, as summarized in Table 6. Industrial Applications of Carbon Black The table below highlights CB's diverse roles, benefits, and contributions across industries, supported by recent research:

Table 6. Mechanical properties of natural rubber composites reinforced with different carbon black grades [60].

CB Grade	Tensile Strength (MPa)	Elastic Modulus (MPa)	100% Modulus (MPa)	Elongation at Break (%)
N220/NR	14.96 ± 1.21	5.16 ± 0.25	2.93 ± 0.12	441 ± 21
N330/NR	12.70 ± 0.92	5.11 ± 0.22	2.90 ± 0.13	387 ± 12
N550/NR	11.05 ± 1.03	4.15 ± 0.31	2.80 ± 0.19	348 ± 30
N774/NR	11.62 ± 1.90	3.78 ± 0.29	2.20 ± 0.09	424 ± 10

3.2.1. UV Stabilization Mechanism of Carbon Black

Carbon black (CB) is widely recognized as a highly effective ultraviolet (UV) stabilizer in polymeric materials, offering robust protection against photo-oxidative degradation. Its efficacy stems from a dual mechanism: (1) absorption of high-energy UV radiation (290–400 nm) by aromatic structures within CB, which converts the energy into harmless thermal dissipation, and (2) scattering of incident UV rays by CB's particulate network, thereby reducing radiation penetration depth. Together, these mechanisms achieve >95% UV-blocking efficiency, significantly prolonging the service life of polymer composites exposed to sunlight [65].

i. Factors Influencing UV Protection

- **Particle Size and Dispersion:** CB's UV-shielding performance is directly linked to its primary particle size (10–100 nm) and dispersion quality. Smaller, uniformly dispersed particles provide more comprehensive coverage, enhancing both absorption and scattering effects.
- **Durability Validation:** Outdoor weathering studies demonstrate the superiority of CB-filled

polymers. For instance, CB-reinforced polyethylene retains 85–90% of its tensile strength after five years of sun exposure, compared to just 40–50% for unfilled counterparts [65].

3.2.2. Thermal Stability Enhancement by Carbon Black

Carbon black (CB) is a highly effective additive for enhancing the thermal stability of polymer composites, offering multi-faceted protection against high-temperature degradation. Studies by Patel and Desai [14] demonstrate that incorporating CB can elevate the degradation onset temperature by up to 30°C in fiber-reinforced polymers (FRPs). This improvement is attributed to three key mechanisms:

- **Thermal Energy Redistribution:** CB's conductive network absorbs and dissipates heat, reducing localized overheating and delaying thermal degradation.
- **Oxygen Diffusion Barrier:** The physical presence of CB particles impedes oxygen penetration, shielding vulnerable polymer chains from oxidative breakdown.
- **Crosslinking Participation:** During vulcanization, CB actively contributes to forming thermally stable network structures, as evidenced by increased crosslink density in AEM/CCB vulcanizates at higher CB loadings, and it is shown in Figure 9 [66, 67].

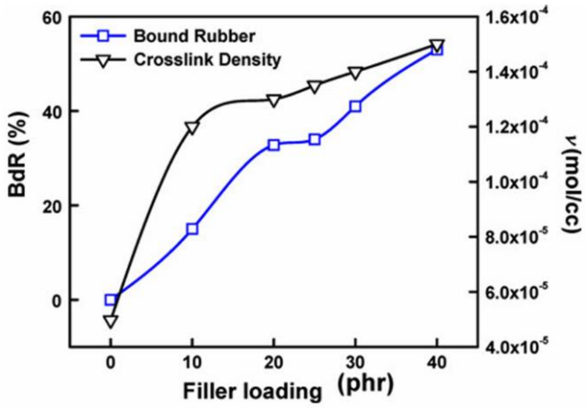

Figure 9. Bound Rubber and Crosslink Density in AEM and AEM/CCB Vulcanizates [67]

3.2.3. Multifunctional Hybrid Composites

Carbon black (CB) serves as a cost-effective performance enhancer in hybrid nanocomposites when combined with advanced nanofillers like carbon nanotubes (CNTs) or graphene, creating ternary systems with remarkable synergistic effects. By bridging the more expensive nanofillers, CB forms enhanced percolation networks that yield significant property improvements, including a 2–3 order magnitude increase in electrical conductivity, 20–40% higher tensile modulus, and 15–25°C improvement in heat distortion temperature compared to single-filler systems [68][69][70]. However, optimizing these composites requires addressing three key challenges: (1) dispersion control to prevent CB-induced nanofiller agglomeration, (2) interface modification for optimal stress transfer, and (3) maintenance of an optimal CB-to-nanofiller loading ratio between 1:1 and 1:3. Recent advances demonstrate that surface-treated CB grades can reduce embrittlement effects by up to 30% while preserving the hybrid performance benefits [72–74], making these multifunctional composites particularly promising for demanding aerospace components and advanced electronics packaging where combined electrical, mechanical, and thermal properties are crucial for reliability and performance.

3.2.4. Carbon Black as a Multi-Functional Reinforcement in Polymer Composites

Carbon black (CB) has emerged as a critical multifunctional additive in polymer composites, delivering simultaneous enhancements in mechanical, environmental, and thermal performance. Its unique percolated network structure acts as an exceptional reinforcing agent, improving tensile strength by 50-300% and reducing wear rates by 30% in tire applications through optimized stress transfer and restricted polymer chain mobility [75,76]. Beyond mechanical reinforcement, CB provides superior UV protection via radiation absorption (200-400 nm) and free radical scavenging, with field studies showing CB-filled EPDM retaining >75% of its original mechanical properties after ten years of environmental exposure - a characteristic particularly valuable for roofing membranes and construction materials [71]. The material further demonstrates excellent thermal stabilization and chemical resistance, enabling applications in high-temperature environments and fuel systems. Recent innovations in sustainable bio-derived CB and AI-optimized formulations are expanding its utility while addressing environmental concerns, particularly in high-performance tires, industrial conveyor belts, and long-life construction materials where durability-weatherability-performance balance is paramount [72]. Ongoing advancements in hybrid filler systems and surface-modified CB grades continue to evolve CB's role in advanced composites, maintaining its relevance through synergistic combinations of traditional reinforcement capabilities and emerging sustainable technologies.

3.2.5. Electrical Conductivity Enhancement in Polymer Composites

Electrical conductivity (percolation threshold 0.5-10 wt%)

Carbon black (CB) has proven to be a highly effective conductive filler for insulating polymer matrices, offering precise tunability of electrical properties through controlled formulations.Its remarkable ability to form percolation networks at ultralow loadings is exemplified in fiber-reinforced polymer (FRP) composites, where electrical percolation occurs at just 0.58 wt% CB loading [54]. The conductivity performance is governed by three critical factors: (1) dispersion quality throughout the matrix, (2) particle morphology and surface characteristics, and (3) spatial distribution efficiency for optimal network formation [73][74][75]. Recent breakthroughs in hybrid systems demonstrate exceptional synergy between CB and carbon nanotubes (CNTs), with the addition of merely 0.2% CB to 0.2% CNT composites boosting conductivity by six orders of magnitude relative to single-filler systems and it is shown in Figure 10, [76]. This significant enhancement arises from CB particles effectively bridging CNT networks to establish robust three-dimensional conductive pathways without compromising polymer processability. Such advanced conductive composites have become indispensable for critical applications including electrostatic discharge (ESD) protection, electromagnetic interference (EMI) shielding, and self-regulating heating elements, where the combination of controlled conductivity and manufacturing practicality is paramount.

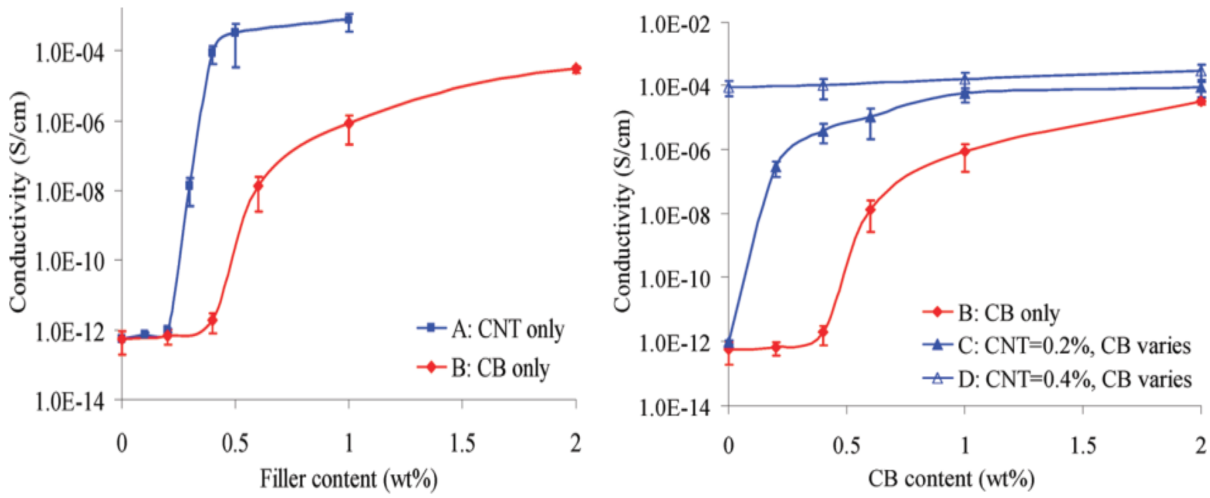

Figure 10. Electrical Conductivity of CNT/CB Hybrid Nanocomposites [93]

4. CARBON BLACK IN ADVANCED INDUSTRIAL APPLICATIONS

4.1. Automotive Manufacturing: Performance and Sustainability Enhancements

Carbon black (CB) plays a fundamental role in automotive manufacturing, particularly in tire production where it delivers critical performance enhancements as a reinforcing filler. In tire applications, CB improves three essential characteristics: durability (30-50% lifespan extension through superior abrasion resistance), safety performance (maintained wet/dry traction across -30°C to 50°C temperature ranges), and rolling resistance (15-20% reduction in energy loss for improved fuel efficiency) [77]. These benefits stem from CB's unique ability to form strong interfacial bonds with rubber polymers, dissipate heat during dynamic loading, and create wear-resistant composite structures. Beyond tires, CB significantly enhances under-hood components - extending timing belt service life by 40% through cyclic stress reinforcement, providing thermal stabilization up to 150°C in radiator hoses, and maintaining seal integrity in gasket materials via chemical resistance to oils and fuels.

Recent advancements in surface-modified CB grades have further improved performance while addressing sustainability through reduced rolling resistance in eco-tires, bio-based rubber compatibility, and enhanced recyclability. These innovations establish CB as a key enabler of next-generation automotive technologies, including EV-specific tire formulations, lightweight composites, and sustainable manufacturing processes [77]. Ongoing research focuses on nano-engineered CB morphologies for targeted property enhancement and AI-optimized compound designs, ensuring CB's continued relevance in meeting evolving automotive standards for safety, performance, and environmental compliance.

4.2. Advanced Paints and Coatings: Multifunctional Performance

Carbon black (CB) serves dual critical functions in advanced coatings technology, acting as both a superior pigment and a performance-enhancing additive. As the most effective black colorant available, CB delivers deep, jet-black coloration with exceptional opacity and tinting strength. Beyond its aesthetic qualities, CB substantially improves coating performance by providing UV stabilization to protect binders from solar degradation, thermal resistance maintaining integrity at temperatures up to 300°C, and weather durability that extends exterior coating lifespan by 30-50%. These multifunctional properties make CB indispensable for demanding coating applications, particularly in high-temperature industrial environments (pipelines, reactors), automotive OEM and refinish systems, and architectural coatings designed for harsh climatic conditions. Recent developments in surface-modified CB grades have further enhanced formulation capabilities by improving dispersion stability and reducing viscosity-related processing challenges [78]. The combination of CB's unparalleled coloration properties and functional performance enhancements continues to make it a vital component in advanced coating systems across multiple industries.

4.3. Carbon Black in Advanced Electronics and Conductive Applications

Carbon black (CB) has become an essential component in modern electronics, effectively converting insulating polymers into functional conductive materials through its unique capacity to establish percolation networks at remarkably low loadings (2-10 wt%). This fundamental property enables critical applications ranging from static-dissipative components in electronic housings and cleanroom equipment to electromagnetic interference (EMI) shielding in gaskets, adhesives, and battery electrodes. The material's versatility has recently propelled its adoption in next-generation technologies, including flexible printed electronics achieving 10-100 S/m conductivity, hybrid transparent conductive films combining CB with indium tin oxide (ITO), and advanced touch sensor interlayers. These innovations underscore CB's dual value as both an economical solution for conventional electronics and a key enabler of emerging technologies [79]. Looking ahead, ongoing research focuses on further refining CB's tunable conductivity and processability to meet the evolving demands of advanced electronic devices.

4.4. Carbon Black in Printing and Packaging Systems

In printing and packaging applications, carbon black (CB) delivers unparalleled performance through its combination of aesthetic and protective properties. As the premier black pigment, CB provides intense, jet-black coloration characterized by exceptional opacity and lightfastness. Beyond its visual qualities, CB offers vital functional benefits including strong UV absorption across the 200-400 nm spectrum, effectively shielding light-sensitive products from degradation. The material's superior dispersion stability ensures consistent print quality and reliable performance in high-volume production environments. Recent advancements in surface-treated CB grades have further enhanced these properties while improving compatibility with modern high-speed printing and coating systems [80, 81]. These characteristics collectively establish CB as an indispensable component in premium printing inks and specialized packaging films where both visual appeal and product protection are paramount.

4.5. Carbon Black in Environmental and Energy Applications

Carbon black (CB) has emerged as a versatile material for sustainable technologies, leveraging its exceptional physicochemical properties to address environmental challenges and it is reported in Table 7.

With an extensive surface area range (20-1500 m^2/g), CB functions as a highly efficient adsorbent in purification systems, achieving >90% removal efficiency for volatile organic compounds and particulate matter in industrial air/water filtration. Simultaneously, its electrical conductivity (10-1000 S/m) and porous architecture make it invaluable for electrochemical energy storage, where it enhances charge transfer in lithium-ion battery anodes and boosts capacitance in supercapacitor electrodes. Recent innovations have further expanded CB's environmental utility through bio-derived variants and surface modifications that improve sustainability without compromising performance. These developments position CB as a dual-purpose solution that bridges pollution control and renewable energy applications, particularly in advanced filtration systems and next-generation energy storage devices [82].

Table 7. Industrial Applications of Carbon Black [60–67]

Sector	Benefits	Key Contributions	Author(s)
Aerospace	Mechanical strength, durability	Enhances structural integrity and wear resistance in high-stress environments	I. Served and C. Us [99]
Boat Coatings	UV shielding, anti-fouling	Protects against marine biofouling and photodegradation	Weber et al. [100]
Home Appliances	Aesthetics, impact resistance	Provides sleek finishes and scratch-resistant surfaces	Cristian I. Contescu [100]
Computer Cases	Thermal/electrical conductivity	Improves heat dissipation and electromagnetic interference (EMI) shielding	Nguyen et al. [36]
Furniture	UV protection, styling	Enhances longevity and design flexibility for outdoor and indoor use	I. Durability [101]
Electronics	Heat and charge management	Optimizes thermal and electrical performance in devices	T. D. Guide and P. Coatings [102]
General Industry	Strength, cost-efficiency	Reduces wear and production costs in machinery and tools	I. Durability [101]
Naval Industry	Corrosion resistance	Shields marine structures from saltwater-induced degradation	Raj [103]
Rubber (Non-Automotive)	Strength, flexibility	Extends product lifespan in dynamic applications (e.g., seals, footwear)	Neethirajan et al. [104]
Packaging Films	UV protection, barrier enhancement	Preserves product integrity and reduces spoilage in food and medical packaging	Ruiz et al. [105]

Table 8. Carbon Black-Polymer Composites: Formulations, Properties, and Applications

Author(s)	Polymer Matrix	CB Loading (wt%)	Key Improvements	Hybrid Systems	Applications	Research Gaps
Barra et al. [107]	Epoxy, PEEK	5–15	+200% flexural strength	–	Aerospace structures	UV degradation mechanisms
P.Tangudom, et al.[108]	SBR, NR	25–35	50% wear resistance (vs. unfilled)	CB + silica (tires)	Automotive tires	Recyclability optimization
Costa et al. [71]	EPDM	20–30	Heat resistance (150°C stable)	–	Engine gaskets	Long-term fluid exposure
Tamošaitienė et al. [72]	PP	10–20	Antistatic (10^4–10^6 Ω/sq)	CB + CNT (0.2%)	Electronics packaging	Dispersion in thin films
Choi et al. [109]	PVDF	15–25	Electrode conductivity (+300%)	CB + graphene	Battery anodes	Cycle life enhancement
Ihueze et al. [110]	HDPE	15–30	Burst strength (+40%)	–	Pressure pipes	Joining techniques
Mistry et al. [111]	PU	5–15	UV shielding (95% blockage)	CB + TiO_2	Roof coatings	Color neutrality
da Silva et al. [112]	PET	8–12	Static dissipation (10^6 Ω/sq)	–	Medical packaging	Sterilization compatibility
Parveez et al. [113]	PEEK	10–20	Flame retardancy (UL94 V-0)	CB + nanoclays	Aircraft interiors	Smoke suppression
Suwasono et al. [114]	Vinyl ester	15–25	Saltwater corrosion resistance	CB + glass fibers	Marine coatings	Biofouling prevention

With an extensive surface area range (20-1500 m²/g), CB functions as a highly efficient adsorbent in purification systems, achieving >90% removal efficiency for volatile organic compounds and particulate matter in industrial air/water filtration. Simultaneously, its electrical conductivity (10-1000 S/m) and porous architecture make it invaluable for electrochemical energy storage, where it enhances charge transfer in lithium-ion battery anodes and boosts capacitance in supercapacitor electrodes. Recent innovations have further expanded CB's environmental utility through bio-derived variants and surface modifications that improve sustainability without compromising performance. These developments position CB as a dual-purpose solution that bridges pollution control and renewable energy applications, particularly in advanced filtration systems and next-generation energy storage devices [82].

5. CHALLENGES AND FUTURE TRENDS IN CARBON BLACK-POLYMER COMPOSITES

The development of carbon black (CB)-polymer composites faces several key challenges and opportunities. Dispersion and agglomeration issues remain persistent obstacles, as van der Waals forces between CB particles often lead to poor distribution within polymer matrices, negatively impacting mechanical, thermal, and electrical properties [82,84]. Health and environmental concerns surrounding CB production continue to drive regulatory changes, particularly regarding emissions and worker exposure to potentially carcinogenic particles [85]. In response to sustainability demands, recovered carbon black (rCB) from end-of-life tires via pyrolysis has emerged as a promising circular economy solution, though its commercial viability is still being established [86]. Bio-based alternatives derived from renewable biomass sources like lignin and coconut shells are under development but face challenges in scaling and cost-competitiveness [87]. Surface functionalization of CB through various modification techniques shows potential for improving polymer compatibility and composite performance [88]. The development of hybrid filler systems combining CB with carbon nanotubes, graphene, or metal oxides offers opportunities to create multifunctional composites with enhanced properties like EMI shielding and mechanical reinforcement [89]. These advancements are driving innovation across multiple technology readiness levels (TRLs), with some solutions like rCB and functionalized CB nearing commercialization (TRL 5-7), while more novel approaches like bio-based CB remain in earlier development stages (TRL 4-5)[90]. The field continues to evolve through a combination of technological innovation, regulatory pressures, and sustainability imperatives.

6. CONCLUSION

Carbon black (CB) has emerged as a highly effective additive for enhancing polymer matrix composites (PMCs), offering significant improvements in mechanical, electrical, and thermal properties. Its incorporation into fiber-reinforced polymers (FRPs) has enabled the development of lightweight, conductive, and high-performance materials with applications across aerospace, automotive, and electronics industries. Studies demonstrate that CB can achieve electrical percolation at remarkably low loadings (as low as 0.58 wt%) while increasing mechanical strength by 15-40%. Furthermore, hybrid systems combining CB with nanomaterials such as graphene or carbon nanotubes exhibit superior multifunctionality, including exceptional electromagnetic interference (EMI) shielding exceeding 150 dB.

Despite these advantages, key challenges hinder widespread industrial adoption. Achieving uniform CB dispersion, ensuring scalable processing, and assessing long-term durability remain critical hurdles. Additionally, environmental and health concerns associated with traditional CB production call for sustainable alternatives. Emerging approaches—such as bio-derived CB, plasma functionalization, and machine learning-assisted optimization—present viable solutions to these challenges. Future research should prioritize standardized processing techniques, advanced characterization methods, and eco-friendly production to fully unlock CB's potential.

Looking ahead, the integration of CB into smart composites and additive manufacturing opens new possibilities for next-generation materials. Interdisciplinary collaboration will be essential to refine material design, enhance performance, and facilitate industrial scalability. By addressing current limitations and leveraging cutting-edge technologies, CB-reinforced composites can drive transformative advancements in high-performance engineering applications, solidifying their role in the future of material science.

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IZVOD

POLIMERNI KOMPOZITI OJAČANI UGLJENIČNOM ČAĐI: MULTIFUNKCIONALNI NAPREDAK, KARAKTERIZACIJA I INDUSTRIJSKA PRIMENA

Ugljenična čađ (CB) se pojavila kao transformativni aditiv u polimernim matričnim kompozitima (PMC), nudeći nenadmašna poboljšanja mehaničkih, električnih i termičkih svojstava. Ovaj sveobuhvatni pregled sintetiše najnovija dostignuća u oblasti kompozita ojačanih CB-om, fokusirajući se na njihove multifunkcionalne uloge u vazduhoplovstvu, automobilskoj industriji, elektronici i energetskim primenama. Ključni nalazi ističu sposobnost CB-a da postigne električnu perkolaciju pri ultraniskim opterećenjima (0,58 težinskih%), poboljša zateznu čvrstoću za 15–40% i omogući zaštitu od elektromagnetnih smetnji (EMI) veću od 150 dB u hibridnim sistemima sa ugljeničnim nanocevima (CNT) ili grafenom.

Pregled sistematski ispituje mehanizme ojačavanja CB-a, uključujući njegovu fraktalnu agregatnu strukturu, međupovršinsku adheziju i sinergijske efekte u hibridnim kompozitima. Razmatraju se kritične primene kao što su lagana EMI zaštita, premazi otporni na UV zračenje i provodljivi lepkovi, uz industrijske izazove poput uniformnosti disperzije i dugotrajne izdržljivosti. Novi trendovi u održivim alternativama (npr. bio-izvedeni karbonski ugljenik, reciklirani karbonski ugljenik iz guma) i naprednoj proizvodnji (npr. 3D štampanje) istaknuti su kao putevi za rešavanje ekoloških problema i ograničenja skalabilnosti.

Uprkos svojoj svestranosti, i dalje postoje izazovi u optimizaciji interfejsa karbonskog ugljenika i polimera, smanjenju zdravstvenih rizika i standardizaciji tehnika obrade. Budući pravci istraživanja naglašavaju dizajn materijala vođen veštačkom inteligencijom, funkcionalizaciju površine i pristupe cirkularnoj ekonomiji kako bi se otključao puni potencijal karbonskog ugljenika u pametnim kompozitima sledeće generacije. Ovaj pregled ističe ključnu ulogu karbonskog ugljenika u unapređenju visokoperformansnih materijala, istovremeno pozivajući na interdisciplinarnu saradnju kako bi se premostile laboratorijske inovacije sa industrijskom primenom.

Ključne reči: *Čađ, polimerni kompoziti, EMI zaštita, hibridni nanokompoziti, električna provodljivost, održivi materijali.*

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