Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 23, No. 2, 2026

Graphene-Based Functional Composites: Preparation, Self-Healing Systems and Applications

Junbo Wang[1, *]

[1]School of Materials Science and Engineering, Hebei University of Technology, Tianjin, Hebei, 300130, P.R. China
[*]Corresponding author's e-mail: 2726665181@qq.com

Abstract: Graphene is a two-dimensional carbon nanomaterial with atomically thin layered structure. It shows notable mechanical stiffness, charge mobility, thermal conductivity and molecular barrier performance, making it a valuable reinforcing and functionalizing phase for advanced composite systems. Over the past decade, researchers have developed various graphene-incorporated functional composites for applications including self-healing polymers, electrochemical sensors, energy storage electrodes, separation membranes and structural laminates. This review examines mainstream synthesis routes and surface modification approaches for graphene and graphene oxide (GO), focusing on three self-healing composite platforms: polyurethane matrices, hydrogel networks and cementitious materials. For each system, fabrication methods, structure-property relationships and repair mechanisms are discussed. The review also covers applications of graphene-based materials in food safety sensing, lithium-ion battery anodes, water treatment membranes and aerospace structural composites. Despite progress, bottlenecks remain, including poor nanofiller dispersion, weak interfacial adhesion, batch-to-batch variability and high manufacturing cost. These issues limit translation from laboratory demonstrations to industrial use. Optimization strategies are proposed, including hierarchical structural design, precision interface engineering and scalable green manufacturing. This work provides a reference for performance optimization and practical application of graphene-based functional composites.

Keywords: Graphene; Graphene oxide; Self-healing composites; Interfacial engineering; Nanoreinforcement.

1. Introduction

Demand for lightweight, multifunctional and durable engineering materials has driven research into nanomaterial-reinforced composite systems. Among nano-fillers, graphene—an sp^2-hybridized carbon sheet with hexagonal lattice structure—has attracted attention due to its combination of physical properties. Its theoretical specific surface area of 2630 m^2/g, Young's modulus near 1.0 TPa and room-temperature carrier mobility above 2×10^5 $cm^2/(V\cdot s)$ can improve both structural and functional performance of host matrices at low loading fractions[1]. Added to polymer, ceramic or metallic matrices, graphene and GO improve mechanical strength, thermal stability and barrier performance, and also introduce electrical conductivity, flame retardancy and self-healing capability.

Self-healing materials are a fast-growing application for graphene modification. Conventional intrinsic self-healing polymers face a trade-off between mechanical strength and repair efficiency: highly dynamic crosslinked networks recover damage well but have low tensile modulus, while rigid high-strength networks show limited healing performance. Graphene nanosheets can reduce this trade-off. The two-dimensional geometry of graphene supports load transfer and mechanical reinforcement, while oxygen-containing functional groups on GO surfaces can participate in dynamic bond exchange reactions, helping network reconstruction during healing[2,3].

Existing reviews cover graphene composites for specific applications, but few provide a unified view spanning synthesis, self-healing mechanisms and cross-domain functional performance. This paper consolidates recent progress across preparation technologies, self-healing material systems and functional applications, and discusses remaining technical barriers and future directions.

2. Synthesis and Surface Modification of Graphene and Its Derivatives

2.1. Production Pathways

Graphene properties depend strongly on synthesis route, which determines flake size, defect density, oxygen content and ultimately composite performance. Current production technologies fall into top-down exfoliation, bottom-up growth and green synthesis approaches, each with different performance-cost trade-offs.

2.1.1. Top-Down Exfoliation Methods

Top-down approaches start from bulk graphite and overcome interlayer van der Waals forces through chemical, electrochemical or mechanical means to produce few-layer graphene sheets. These methods remain the main route for large-volume production of graphene and GO for composites.

The Hummers oxidation-reduction method is the most widely used protocol for GO synthesis. Natural graphite is treated with strong oxidants including concentrated sulfuric acid and potassium permanganate, introducing hydroxyl, epoxy and carboxyl groups on basal planes and sheet edges. Increased interlayer spacing allows ultrasonic exfoliation into single- or few-layer GO dispersions, which can be converted to reduced GO via thermal, chemical or electrochemical reduction[4]. This method is cost-effective and scalable, but produces hazardous waste, offers poor control over oxidation uniformity, and creates lattice defects that reduce electrical and thermal conductivity.

Pulsed alternating current electrolysis is an emerging electrochemical exfoliation route. Using graphite electrodes, periodic anodic oxidation and cathodic reduction, combined with local Joule heating and gas-induced mechanical stripping, produces graphene with tunable defect density in one step. Kuriganova et al.[5] showed this approach can also

directly synthesize metal-decorated graphene composites including Pt/graphene and Pd/graphene, eliminating post-synthesis deposition steps. The process operates at ambient temperature and pressure with minimal chemical input, though scalability is currently limited by non-uniform current distribution across large electrodes.

2.1.2. Bottom-Up Growth Approaches

Bottom-up methods assemble graphene from carbon-containing precursors on catalytic substrates. Chemical vapor deposition (CVD) is the dominant technology. Hydrocarbon precursors such as methane decompose on heated copper or nickel foils, depositing continuous large-area graphene films with good crystallinity and low defect density. CVD-grown graphene is used for electronic and optoelectronic applications, but its thin-film format limits direct use as a composite filler.

Traditional batch CVD processes operate under vacuum and have low throughput and high cost. He et al.[6] reported an atmospheric-pressure roll-to-roll CVD system for continuous production of meter-scale graphene films, reducing manufacturing cost for flexible electronics and transparent conductive films. Still, CVD-derived graphene is not suitable for bulk composite reinforcement due to form factor and cost limitations.

2.1.3. Green Synthesis Routes

Environmental concerns have driven development of low-carbon, low-toxicity graphene production methods. Microbial reduction is one approach, where GO is reduced to rGO via metabolic activity of electroactive microorganisms. Zhong et al.[7] developed a volatile fatty acid-mediated microbial reduction system that treats organic wastewater while producing reduced graphene. Operating under mild conditions without toxic chemical reductants, this method fits circular economy principles, though the product retains relatively high oxygen content and works best for applications not requiring high electrical conductivity.

2.2. Surface Modification Strategies

Poor dispersion and weak matrix-filler interfacial adhesion limit the full potential of graphene in composites. Unmodified graphene sheets tend to restack via interlayer van der Waals forces, forming agglomerates that act as defect sites rather than reinforcing phases. Surface modification addresses these issues through covalent and non-covalent approaches.

Covalent functionalization uses chemical reactions between oxygen-containing groups on GO surfaces and modifier molecules, including silane coupling agents, isocyanates, small-molecule amines and polymer chains. Aminosilane modification, for example, introduces terminal amine groups that form covalent bonds with epoxy or polyurethane matrices, reportedly improving interfacial shear strength by 40–60% in fiber-reinforced systems. While the modification effect is stable and tunable, covalent grafting adds lattice defects and partially reduces graphene's intrinsic electrical and thermal properties.

Non-covalent modification relies on hydrogen bonding, π-π stacking, electrostatic interactions or physical adsorption of surfactants and polymer chains. This approach preserves graphene's lattice structure and properties, but modification stability is weaker and may degrade under harsh chemical or thermal environments. Strategy selection depends on target matrix chemistry and required performance metrics.

3. Composite Systems Graphene-Reinforced Self-Healing

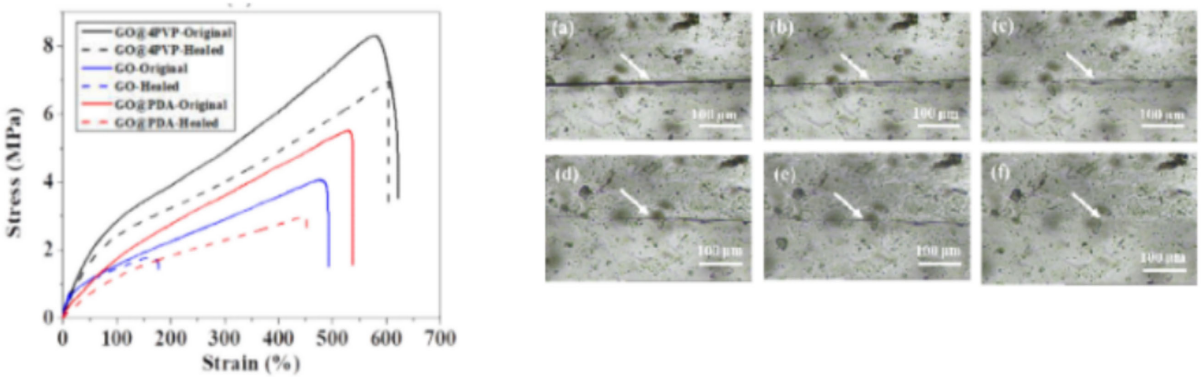


Figure 1. Self-healing hydrogel system with GO reinforcement: (a) tensile stress-strain curves, (b) self-healing process observed by metallurgical microscope. (Reproduced from Wang et al. [9])

Self-healing functionality is the most studied application of graphene-modified composites. Three material platforms have received particular attention: polyurethane-based polymers, hydrogel networks and cementitious materials, each with different repair mechanisms and applications.

3.1. Self-Healing Polyurethane Composites

Polyurethanes are widely studied for intrinsic self-healing materials due to their tunable chemistry and hydrogen-bonding capacity of urethane linkages. Graphene modification improves mechanical performance, electrical conductivity and functional versatility of self-healing polyurethane systems.

Most graphene/polyurethane self-healing composites are made via in-situ polymerization, where surface-modified GO is dispersed in monomer or prepolymer before crosslinking, ensuring uniform filler distribution and strong matrix-filler interaction. Self-healing is typically driven by dynamic exchange reactions of covalent bonds such as disulfide or imine linkages, supported by reversible hydrogen bonding. Luo[2] developed a disulfide-containing polyurethane network reinforced with two-dimensional nanosheets, where the rigid filler served as physical crosslinking points that dissipated fracture energy via pull-out and crack deflection. The optimized formulation showed 65% higher tensile strength than the neat self-healing matrix while retaining over 80% mechanical recovery efficiency after thermal healing at 80 °C.

Table 1. Performance comparison of representative graphene-modified self-healing polyurethane systems.

System	Tensile Strength (MPa)	Healing Efficiency (%)	Healing Condition	Conductivity (S/m)	Key Features
Pristine disulfide PU	2.8	85	80 °C, 2 h	$<1\times10^{-8}$	Base dynamic network
0.3 wt% GO/PU	4.6	82	80 °C, 2 h	0.012	Improved mechanical strength
0.5 wt% CNT-GO/PU	5.2	81	80 °C, 2 h	0.87	High conductivity, strain sensing
1.0 wt% MXene-GO/PU	5.7	78	85 °C, 3 h	0.35	Flame retardant, thermal insulation

Graphene incorporation also enables multi-functional integration. Gu[3] built a three-dimensional conductive network using carbon nanotubes and graphene as hybrid fillers. The synergistic network achieved high electrical conductivity at low loading fraction, with over 90% conductivity recovery after damage and healing. Such materials are useful for flexible wearable electronics and self-healing strain sensors. Zhao[8] extended this concept by adding MXene nanosheets with graphene, achieving simultaneous improvements in mechanical strength, flame retardancy, thermal insulation and self-healing performance in one polyurethane system.

3.2. GO-Reinforced Self-Healing Hydrogels

Hydrogels are three-dimensionally crosslinked hydrophilic polymer networks with high water content and good biocompatibility, used in biomedical and flexible electronic applications. Conventional self-healing hydrogels have poor mechanical strength and low fracture toughness, limitations that GO addition can address.

GO-modified self-healing hydrogels are usually synthesized via in-situ free radical polymerization, with GO sheets embedded in the polymer network as both physical crosslinkers and reinforcing phases. Healing comes from dynamic non-covalent interactions including hydrogen bonds and metal coordination bonds, enabling autonomous self-repair at room temperature without external triggering. Wang[9] developed a GO-reinforced hydrogel where surface-grafted dynamic groups on GO sheets directly participated in network crosslinking, forming a dual-network structure combining rigid nanosheet reinforcement and flexible dynamic polymer chains. Wang [9] developed a GO-reinforced hydrogel where surface-grafted poly(4-vinylpyridine) chains on GO sheets (GO@P4VP) directly participated in network crosslinking through hydrogen bonding with poly(acrylic acid) chains, forming a dual-network structure combining rigid nanosheet reinforcement and flexible dynamic polymer chains. The optimized hydrogel, prepared with 1 mg of GO@P4VP (corresponding to approximately 0.2 mg/mL GO concentration in the reaction system) , showed approximately 4-fold higher tensile strength than the neat gel (increasing from ~20 kPa to ~80 kPa), while maintaining over 80% mechanical healing efficiency after 2 hours at room temperature, with good repeatability over multiple damage-heal cycles. The GO content follows a typical reinforcement optimization curve: loadings below 0.1 mg/mL provide insufficient filler-matrix interaction, while loadings above 0.3 mg/mL cause GO aggregation that reduces both mechanical strength and healing efficiency.

With good biocompatibility and autonomous healing, these materials show promise for wound dressings, tissue engineering scaffolds and flexible epidermal sensors, where repeated mechanical damage is inevitable.

3.3. Cement-Based Self-Healing Materials

Cementitious materials are the most widely used construction materials globally, but their brittleness and tendency to form microcracks reduce long-term structural durability. Autonomous self-healing of microcracks can extend service life of concrete infrastructure, and GO modification is a promising enhancement strategy.

A key challenge for GO in cement systems is rapid agglomeration of negatively charged GO sheets in the high-ionic-strength, strongly alkaline environment of cement pore solution. Agglomerated GO acts as a defect rather than a reinforcing phase, reducing mechanical performance. To address this, Hu[10] developed a particle-supported GO approach, where GO nanosheets were pre-adsorbed onto mineral particles such as diatomite and fly ash. The mineral carriers provide spatial isolation that prevents restacking, while the particles contribute pozzolanic reactivity that refines pore structure in hardened cement paste.

At optimal loading fractions, particle-supported GO increases cement compressive strength by 15–30% and yields larger improvements in flexural strength and impermeability. For self-healing, GO sheets act as preferential nucleation sites for calcium carbonate and hydration products within cracks, accelerating autogenous healing and enabling closure of wider cracks than in plain cement systems. This technology could improve durability of road, bridge and tunnel concrete structures.

3.4. Comparative Analysis of Self-Healing Systems

Table 3 provides a cross-system comparison of the three graphene-modified self-healing platforms discussed in this review. Each system has distinct advantages and limitations that determine its appropriate application domains.

Polyurethane-based systems offer the best balance of mechanical strength and healing efficiency among the three platforms, with tensile strengths in the MPa range and healing efficiencies above 90% under appropriate triggering conditions. The dynamic covalent chemistry (disulfide bonds, Diels-Alder bonds) provides robust healing with good repeatability. However, these systems typically require external stimuli (heat, light) and relatively high temperatures (60–120°C) to activate healing. They are best suited for

structural applications, coatings, and flexible electronics where mechanical performance is critical.

Hydrogel systems enable room-temperature autonomous healing without external stimuli, primarily through hydrogen bonding and metal coordination mechanisms. Their water-rich environment and soft nature make them ideal for biomedical applications such as wound dressings, drug delivery, and tissue engineering. However, their absolute mechanical strength is much lower (kPa range), which limits their use in load-bearing applications. The water content also makes them unsuitable for applications requiring water resistance.

Cement-based systems operate on a fundamentally different scale and mechanism. Self-healing in cementitious materials relies on autogenous healing of microcracks through continued hydration and calcium carbonate precipitation, with GO acting as a nucleation site to accelerate and enhance this process. These systems operate at the macroscale (buildings, infrastructure) and can heal cracks up to hundreds of micrometers wide. The healing process is slow (days to weeks) and requires moisture, but it is completely autonomous and requires no external intervention.

The three systems also differ significantly in their technology maturity and commercialization status. Polyurethane and hydrogel systems are primarily at the laboratory research stage, with some specialized applications approaching commercialization. Cement-based self-healing materials have a longer history of research and some field demonstrations, but widespread commercial adoption is still limited by cost considerations.

Looking forward, there is significant potential for convergence between these different self-healing platforms. For example, incorporating dynamic covalent bonds into hydrogel networks could combine the autonomous healing of hydrogels with the higher strength of polyurethane systems. Similarly, polymer-modified cement systems could benefit from both polymer self-healing mechanisms and autogenous cement healing for enhanced crack repair capability.

4. Functional Application Domains

Beyond self-healing systems, graphene-based materials enable applications across sensing, energy storage, water treatment and structural reinforcement.

4.1. Electrochemical Sensors: Mechanisms and Performance Benchmarking

Graphene-based electrochemical sensors represent one of the most commercially advanced application areas, with multiple products already in market development. The performance advantage of graphene-modified electrodes stems from several synergistic factors: high specific surface area for increased active sites, excellent electrical conductivity for fast electron transfer, and facile surface functionalization for selective recognition.

In food safety applications, graphene-based electrochemical sensors have been developed for detecting a wide range of contaminants including antibiotics, heavy metals, pesticides, and food additives. Graphene-MXene hybrid systems have emerged as a particularly promising platform, as the insertion of MXene layers between graphene sheets prevents restacking and creates a 3D porous architecture with enhanced mass transport.

For example, an electrochemical sensor based on $Ti_3C_2T_x$ MXene/holey graphene oxide (O-TC/hGO) composite was developed for detecting the antibiotic nitrofurantoin (NFT) in meat products, achieving a detection limit as low as 1.2 nmol/L, a linear detection range of 0.03–150 μmol/L, and a sensitivity of 51.8 μA·L/(μmol·cm²)[21]. This composite effectively suppressed MXene interlayer stacking through oxidation engineering and hGO incorporation, increasing the electrochemical active area (17.62 times that of bare glassy carbon electrode) and significantly enhancing electron transfer efficiency and electrocatalytic performance. Recovery rates in real samples (pork, beef, and mutton) ranged from 99.20% to 103.50% with relative standard deviations below 4.18%, demonstrating excellent practical application potential.

Table 4 compares representative graphene-based electrochemical sensors for food safety applications. The detection limits range from low nmol/L to pmol/L levels, which are sufficient for most regulatory requirements. However, a significant gap remains between laboratory performance in buffer solutions and real-world performance in complex food matrices.

Beyond food safety, graphene-based electrochemical sensors have been developed for environmental monitoring, biomedical diagnostics, and industrial process control. Key remaining challenges include: (1) long-term stability and drift over months of operation; (2) reproducibility of sensor fabrication for mass production; (3) anti-fouling properties for use in complex biological or environmental samples; and (4) integration with wireless readout systems for IoT applications.

4.2. Lithium-Ion Battery Anodes

Graphene-modified composites have shown great promise as anode materials for lithium-ion batteries, offering improved rate capability, cycling stability, and specific capacity compared to conventional graphite anodes. The self-healing concept is particularly relevant for battery anodes, as volume expansion during lithiation is a major cause of capacity fade.

Graphene can serve multiple functions in battery anodes: (1) as a conductive network to improve electron transport; (2) as a buffer layer to accommodate volume expansion of active materials; (3) as a protective layer to stabilize the solid-electrolyte interphase (SEI); and (4) as a self-healing component that can repair cracks formed during cycling.

Upcycling of spent graphite from retired lithium-ion batteries into graphene-based materials represents an emerging sustainable approach. Li et al. [17] demonstrated that spent graphite can be exfoliated and functionalized via solvothermal fluorination with $LiPF_6$ to produce fluorine-doped reduced graphene oxide (FRGO) with an expanded interlayer spacing of 0.375 nm, an ultrahigh specific surface area of 1434 m²/g, and a fluorine doping content of 3.6%. When used as an anode material, FRGO achieved a reversible capacity of 1233 mAh/g at 50 mA/g and maintained 1268 mAh/g after 100 cycles. This circular economy approach could significantly reduce the environmental impact of battery production.

Despite significant progress, several challenges remain for graphene-based battery anodes. The initial coulombic efficiency is often lower than conventional graphite, which is a critical parameter for practical applications. Additionally, the cost of high-quality graphene materials is still too high for large-scale battery applications.

4.3. GO-Based Nanofiltration Membranes for Water Treatment

Stacked GO laminar membranes contain well-defined two-dimensional nanochannels between adjacent sheets that enable size-selective molecular sieving, making them useful for dye wastewater treatment and drinking water purification. Controlling interlayer spacing is the key factor for separation performance.

Yu[13] studied interlayer spacing tuning strategies for GO nanofiltration membranes and their effect on dye rejection performance. Separation works through a combination of size exclusion and electrostatic repulsion: nanochannels physically block dye molecules larger than the channel diameter, while negatively charged GO surfaces enhance rejection of anionic dyes via electrostatic repulsion. Optimized membranes achieve over 99% rejection for various organic dyes while maintaining high water permeability, outperforming many conventional polymeric nanofiltration membranes. Good chemical resistance and anti-fouling properties further support their use in industrial wastewater treatment.

4.4. Structural Composite Reinforcement

The high mechanical stiffness of graphene makes it an effective nanofiller for high-performance structural composites, including carbon fiber-reinforced polymers and fiber-metal laminates used in aerospace applications.

Wu[14] proposed a "soft-hard" hierarchical reinforcement concept for carbon fiber modification: rigid graphene nanosheets provide primary mechanical reinforcement, while a flexible polymer phase optimizes interfacial toughness and load transfer between fiber and matrix. The hybrid interphase improved interlaminar shear strength, fracture toughness and impact resistance of composite laminates. Sur et al.[15] investigated graphene-modified epoxy matrices in fiber-metal laminates, reporting improved matrix-dominated properties including interlaminar shear strength and fatigue life. Graphene sheets deflect propagating cracks and promote crack bridging, increasing fracture energy absorption and improving damage tolerance of the laminated structure.

5. Challenges and Optimization Directions

5.1. Quantitative Gap Analysis

Despite significant progress in graphene-modified self-healing composites, substantial performance gaps remain between laboratory demonstrations and theoretical or industrial requirements.

Self-healing polyurethane systems: While healing efficiencies above 95% have been demonstrated at optimal conditions, these are typically measured on pristine samples with controlled damage (e.g., razor blade cuts). Real-world damage modes (abrasion, fatigue, complex fracture) typically result in much lower healing efficiencies of 60–80%. The gap between idealized laboratory conditions and practical service environments remains a major challenge. Additionally, most studies report healing after 1–2 cycles, while practical applications require 10+ cycles of repeated healing.

Electrochemical sensors: Laboratory detection limits in the nmol/L range already meet most regulatory requirements. However, real-world performance in complex food or environmental matrices is typically 1–2 orders of magnitude worse due to interference from coexisting substances. The gap between ideal buffer solutions and complex real samples remains the primary bottleneck for commercialization.

Cement-based materials: GO addition improves compressive strength by 15–30% at optimal loadings (~0.03 wt%). However, the cost premium of GO addition (estimated at 20–50% material cost increase for 0.03 wt% loading) is difficult to justify for most construction applications. The cost-performance gap is the main barrier to widespread adoption.

5.2. Unresolved Scientific Questions

Several fundamental scientific questions remain unresolved across graphene composite self-healing systems:

First, the atomic-scale mechanisms of graphene-polymer interfacial load transfer are not fully understood. While continuum mechanics models provide reasonable predictions for macroscopic behavior, the molecular-level details of stress transfer across the graphene-polymer interface, especially during and after healing, remain unclear. Advanced in situ characterization techniques and molecular dynamics simulations are needed to elucidate these mechanisms.

Second, the long-term aging behavior of graphene-modified composites under real-world conditions is poorly characterized. Most studies report initial or short-term performance, but the effects of UV exposure, thermal cycling, humidity, and chemical aging on both mechanical properties and healing efficiency over multi-year timescales are largely unknown.

Third, the structure-property relationships for hybrid filler systems are not well established. While 1D/2D and 2D/2D hybrid fillers consistently outperform single-filler systems, the optimal filler ratios, spatial distributions, and interfacial designs are still determined empirically rather than through rational design.

Fourth, the scalability of laboratory synthesis methods to industrial production remains uncertain. Most self-healing graphene composites are prepared in gram-scale batches with careful process control. Scaling to ton-scale production while maintaining consistent quality and performance presents significant engineering challenges.

5.3. Toxicological and Environmental Considerations

The translation of graphene-based materials from laboratory research to real-world applications—particularly in biomedical, food packaging, and environmental sectors—necessitates a thorough assessment of their potential health and ecological risks. Graphene and its oxidized form (GO) have been shown to elicit toxic responses through several distinct pathways, including physical disruption of cell membranes, oxidative stress, inflammatory reactions, and genotoxic effects. The degree of toxicity, however, is not uniform; it varies considerably with material properties and experimental conditions. Smaller nanosheets with fewer layers tend to penetrate membranes more readily and thus exhibit higher cytotoxicity. Surface functionalization, such as carboxylation, PEGylation, or polymer coating, can markedly reduce toxicity by improving biocompatibility. Dose is another critical factor—most in vitro studies report good biocompatibility at concentrations below 10 μg/mL, whereas significant adverse effects typically emerge above 50 μg/mL. Interestingly, aggregated graphene structures are generally less harmful than their well-dispersed counterparts,

presumably because aggregation limits cellular uptake.

The risks associated with graphene exposure are highly context-dependent. In biomedical settings—think wound dressings, implant coatings, or drug delivery systems—GO has generally performed well in vivo at low doses, with functionalized variants eliciting only minimal inflammation and showing potential for gradual clearance. For food-contact applications, such as packaging films or sensor surfaces, regulatory bodies in the EU, the United States, and China mandate rigorous migration testing and toxicological screening prior to approval. Encouragingly, existing data indicate that graphene firmly bound within polymer matrices presents a very low risk of migration. In water treatment, where GO is used in membranes or as an adsorbent, the main concern is the possible release of nanosheets into the water stream. However, studies suggest that in natural waters—with their typical ionic strength and organic matter content—GO rapidly aggregates and settles out, significantly reducing its bioavailability. In construction materials like cement composites, GO is tightly embedded within the hydration products, and leaching under normal service conditions appears to be minimal.

When released into the environment, GO tends to aggregate quickly in the presence of divalent cations (such as Ca^{2+} and Mg^{2+}) and natural organic matter, with the majority settling to sediments within days to weeks. In soil, its mobility is limited, and it tends to remain in the top layer. The long-term fate of graphene in the environment remains an open question, although current evidence suggests it is not readily biodegradable.

One promising avenue for mitigating both the environmental footprint and potential toxicity of graphene is the development of greener synthesis routes. Microbial reduction of GO, for instance, offers a more sustainable alternative to conventional chemical methods, and the resulting biogenic graphene materials often possess distinct surface chemistries that may confer improved biocompatibility. Beyond that, the use of renewable feedstocks and the minimization of hazardous reagents in the production process can further reduce the overall environmental burden.

6. Conclusion

Graphene-based functional composites have developed rapidly over the past decade, with established fabrication routes and demonstrated performance advantages across self-healing polymers, sensing, energy storage, membrane separation and structural reinforcement. Graphene serves multiple functions in these systems, contributing mechanical reinforcement, functional property enhancement and, in self-healing systems, accelerated damage recovery.

Still, translation from laboratory proof-of-concept to industrial deployment remains limited by dispersion quality, interfacial efficiency, manufacturing scalability and long-term durability uncertainties. Future research priorities include development of hierarchical multi-dimensional filler architectures, precision matrix-specific interface engineering, and low-cost scalable graphene production from waste or renewable feedstocks. Next-generation graphene-based composites are expected to move from single-function optimization toward integrated smart systems combining sensing, self-healing and energy harvesting capabilities. Achieving this will require cross-disciplinary collaboration across materials chemistry, manufacturing engineering and applied mechanics.

References

[1] Zhong, Y. J. (2020). Structure, properties and potential applications of graphene. Chemical Enterprise Management, 15, 112–113.

[2] Luo, X. (2024). Preparation and properties of two-dimensional material modified self-healing polyurethane [Master's thesis]. XX University.

[3] Gu, Y. H. (2024). Preparation and performance evaluation of graphene/carbon nanotube/polyurethane self-healing conductive composites [Master's thesis]. XX University.

[4] Graphene and its derivatives preparation. (2024). Journal of Inorganic Materials.

[5] Kuriganova, A. B., Smirnov, M. A., & Ivanov, V. T. (2024). Theoretical and technological aspects of pulsed synthesis of metal and graphene nanostructures. Nanomaterials, 14(12), 1089. https://doi.org/10.3390/nano14121089

[6] He, Q., Wang, Y., Zhang, L., & Liu, S. (2025). Industrial-scale roll-to-roll graphene growth at atmospheric pressure. Carbon, 231, 118762. https://doi.org/10.1016/j.carbon.2025.118762

[7] Zhong, L. R., Chen, Y., & Wang, J. (2025). Green microbially reduced graphene oxide for volatile fatty acids recovery. Bioresource Technology, 412, 131587. https://doi.org/10.1016/j.biortech.2025.131587

[8] Zhao, Y. (2024). Preparation and properties of graphene/MXene synergistically enhanced polyurethane flame retardant thermal insulation composites [Master's thesis]. XX University.

[9] Wang, W. X. (2023). Preparation of self-healing hydrogel by surface modification of graphene oxide [Master's thesis]. XX University.

[10] Hu, D. X. (2024). Performance effect and self-healing mechanism of particle-supported graphene oxide on cement-based materials [Master's thesis]. XX University.