A Mini Review of Conductive Graphene/ Polymer Composites

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Minireview Article

ABSTRACT

Conductive polymer–graphene composites have emerged as a promising class of materials with exceptional electrical, mechanical, and thermal properties, making them highly suitable for applications in flexible electronics, energy storage, and biomedical devices. The unique combination of $\pi - \pi$ interactions and strong interfacial bonding between graphene and conductive polymers enhances charge transport, mechanical strength, and environmental stability. This review provides a comprehensive analysis of recent advancements in the synthesis, processing techniques, and structure-property relationships of these composites. Key focus areas include the role of graphene functionalization, polymer matrix selection, dispersion strategies, and the influence of composite morphology on electrical conductivity. Additionally, we discuss their applications in supercapacitors, sensors, electromagnetic shielding, and next-generation electronic devices. Finally, challenges related to scalability, stability, and fabrication techniques are addressed, along with future perspectives on optimizing these materials for industrial applications.

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1. INTRODUCTION

Carbon-based nanomaterials have garnered significant attention in the development of polymer composites due to their ability to significantly enhance thermal, electrical, and mechanical properties even at relatively low concentrations (Ayanda et al., 2024). These nanocomposites consist of a continuous polymer phase reinforced with carbon-based nanomaterials, such as graphene, carbon nanotubes, and carbon fibers (Islam et al., 2022). The addition of these nanoparticles modifies the composite's properties based on factors such as particle size, physical structure, and the chemical interactions between the nanoparticles and the polymer matrix (Lim et al., 2021). A crucial aspect of these materials' performance is the interfacial layer between the polymer and the nanoparticles, which plays a vital role in governing their structural and dynamic properties at the macroscopic scale (Cheng et al., 2017). Due to their large surface-to-volume ratio, nanoparticles serve as excellent fillers, thereby increasing polymer-nanoparticle interactions and improving the overall composite performance (Dong et al., 2024). However, in the case of graphene-based fillers, strong van der Waals forces can lead to agglomeration, which may create voids and weaken the composite by facilitating crack propagation (Dong et al., 2024, Ayanda et al., 2024).

Conductive polymer–graphene composites offer several advantages over traditional conductive materials. They combine the flexibility, light weight, and processability of polymers with the exceptional electrical conductivity, mechanical strength, and high surface area of graphene. This synergy results in materials that are not only conductive but also more flexible, durable, and easier to fabricate into complex shapes. Additionally, these composites exhibit enhanced corrosion resistance and can be tailored for specific applications, making them ideal for use in flexible electronics, sensors, energy storage devices, and conductive coatings, where traditional metals or ceramics may be too rigid or difficult to process.

Among various carbon-based nanomaterials, graphene has emerged as one of the most promising candidates for conductive polymer composites, owing to its exceptional electrical conductivity, mechanical strength, and chemical stability (Ayanda et al., 2024). Graphene, a monolayer of sp^2-hybridized carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits remarkable properties such as high intrinsic carrier mobility, superior thermal conductivity, and a large surface area, making it ideal for a range of applications (Maharjan and Jayatissa, 2022). These include flexible electronics, supercapacitors, electromagnetic shielding, sensors, and biomedical devices (Preethi et al., 2024)). For instance, graphene-based composites are increasingly being utilized in applications such as wearable sensors, energy storage devices, and smart textiles, due to their superior conductivity and flexibility (Osman et al., 2022). However, challenges remain in fully exploiting graphene's potential in polymer composites, particularly concerning issues such as dispersion, interfacial compatibility, and processability (Kumar et al., 2021).

To overcome these challenges, extensive research has focused on optimizing graphene dispersion and enhancing the compatibility between graphene and polymer matrices through techniques such as functionalization, polymer blending, and surface modification (Mbayachi et al., 2021). Strategies such as chemical functionalization of graphene can improve dispersion and bonding with the polymer matrix, which is essential for enhancing both electrical conductivity and mechanical strength (Olatomiwa et al., 2022).

This review provides an in-depth analysis of the recent advancements in conductive polymer-graphene composites, focusing on fabrication techniques, structure-property relationships, and performance enhancement strategies. Special attention is given to the role of graphene functionalization, polymer selection, and dispersion techniques to optimize the electrical and mechanical properties of these composites. Furthermore, key applications such as energy storage, sensors, and flexible electronics are discussed in detail. The review also highlights the challenges faced in the scalability and industrial implementation of these composites, along with future perspectives on overcoming these obstacles for broader commercial applications.

2. FABRICATION METHODS OF GRAPHENE

The two main production processes for graphene are the bottom-up and the top-down approaches.

The bottom-up approach includes chemical vapor deposition, epitaxial growth, pyrolysis, substrate-free gas-phase synthesis, total organic synthesis, and template route. Bottom-up techniques create graphene and its derivatives by utilizing carbon sources other than graphite. This method employs alternative carbon allotropes, beginning with specific sources and progressing toward the creation of the general graphene. The top-down approach includes the ball milling method, mechanical and electrochemical exfoliation, oxidative exfoliation reduction of GO, arc discharge, liquid-phase exfoliation, and unzipping carbon nanotubes (CNTs) (Kumar et al., 2021). Table 1 below gives a summary of the fabrication methods of graphene and the general advantages and disadvantages of these processes.

The bottom-up and top-down approaches are two primary methods for fabricating graphene, each with distinct processes and benefits. The bottom-up approach involves building graphene from smaller units, such as carbon atoms or molecules, through chemical vapor deposition (CVD) or chemical synthesis. This method allows for precise control over the material's structure, resulting in high-quality graphene with fewer defects. It is particularly suitable for applications requiring high-quality graphene, such as next-gen electronics and sensors, where performance and precision are critical. However, it can be costly and challenging to scale up for large-area production. On the other hand, the top-down approach involves breaking down bulk graphite into graphene sheets using methods like mechanical exfoliation or chemical intercalation. This method is generally more scalable and cost-effective, making it ideal for large-scale production and applications like supercapacitors and EMI shielding, where a larger quantity of graphene with moderate quality is acceptable. While the top-down approach can produce graphene with more defects, it is suitable for applications where cost and scalability are prioritized over ultra-high performance.

Table 1. Summary of the fabrication methods of graphene (Mbayachi et al., 2021, Olatomiwa et al., 2022, Jahdaly et al., 2021)

	Bottom-up approach		Top-down approach		
Basis	Building up of material from the bottom i.e. atom or molecule to get a nanoparticle.		Successive cutting down or grading of bulk material to get nanoparticles.		
Source	CH_4, C_2H_4, C_3H_8 gas/SiC		Graphite		
Processing Method	i. Epitaxial Growth	➢ *Annealing of SiC wafer*	i. Mechanical exfoliation	➢ *Scotch tape* ➢ *AFM tip*	
	ii. Chemical Vapor Deposition (CVD)	➢ *Thermal* ➢ *Plasma*	ii. Chemical Synthesis	➢ *Reduction of GO* ➢ *Sonication*	
			iii. Chemical Exfoliation	➢ *Exfoliation of GIC*	
			iv. Pyrolysis		
Advantages	❖ Cheaper method ❖ Disposition parameters are controllable ❖ Ultrafine nanocomposites ❖ High conductivity ❖ High transparency ❖ High conductivity		❖ Large scale production ❖ Deposition over a large area ❖ No chemical purification is needed. ❖ Low cost ❖ Low defects ❖ Control of deposition		
Disadvantages	❖ Large-scale production is difficult. ❖ Chemical purification of nanocomposites is necessary. ❖ Introduces voids in the transfer process		❖ Broad size distribution ❖ Varied particle shape ❖ Difficulty in removing the surfactant molecules. ❖ Inconsistency in the produced graphene layer		

3. POLYMER SELECTION CRITERIA FOR GRAPHENE-BASED COMPOSITES

The selection of an appropriate polymer matrix is crucial for optimizing the properties of graphene-based composites. Key factors include electrical conductivity, mechanical strength, thermal stability, and processability. The polymer should enable good dispersion of graphene while maintaining strong interfacial adhesion and structural integrity. Conductive polymers like polyaniline (PANI) (Zhang et al., 2010) and polypyrrole (PPy) (Lim et al., 2013) are favored for high electrical conductivity, while polyvinylidene fluoride (PVDF) (Samoei et al., 2024) and polycarbonate (PC) (Wu et al., 2024)) are chosen for their superior mechanical and thermal properties. Epoxy resins offer excellent adhesion and durability, making them suitable for structural applications (Tang et al., 2013). Table 2 provides a comparison of commonly used polymer matrices in graphene-based composites.

Electrical Conductivity (S/m): Conductive polymers like PANI and PPy exhibit higher values, while insulating polymers like PC and Epoxy show much lower conductivity. Mechanical Strength (MPa): Ranges vary depending on polymer grades and composite formulations. Thermal Stability (°C): Defined as the decomposition temperature (Td) where significant degradation begins. Table 2 provides a structured overview of polymer selection for graphene composites based on their key performance characteristics. In addition to the above-mentioned polymer materials, poly (methyl methacrylate) has been also used to synthesis high conductive nanocomposite (Wang and Jayatissa, 2015, Wang and Jayatissa, 2015). Also, recent studies have shown that incorporating polymer blends can further enhance the electrical and mechanical performance of graphene-based composites by optimizing interfacial interactions and phase compatibility (Houa et al., 2022, Itapu and Jayatissa, 2018). In this manuscript, one of the polymers discussed is epoxy. Epoxy is typically classified as a thermoset polymer, widely known for its excellent mechanical and thermal properties, as well as its adhesive strength. While epoxy in its pure form is not conductive, it can exhibit conductivity when modified by incorporating conductive fillers such as graphene, carbon nanotubes, or other carbon-based materials. In this context, epoxy-based composites can be engineered to enhance electrical conductivity, which allows them to be used in various conductive applications.

One of the major challenges associated with the dispersion of graphene in polymer matrices is the strong van der Waals forces between graphene sheets, which lead to agglomeration and the formation of clusters. These clusters reduce the effective surface area and hinder the uniform distribution of graphene within the polymer, limiting the overall properties of the composite. To address this, various strategies can be employed, such as chemical functionalization of graphene to improve its compatibility with the polymer matrix, surface modifications to enhance dispersibility, and the use of ultrasonic treatments or shear mixing during the fabrication process. Additionally, incorporating surfactants or using polymer blends can help achieve a more stable and homogeneous dispersion, ensuring optimal performance of the composite material.

4. APPLICATIONS OF CONDUCTIVE POLYMERS IN ADVANCED TECHNO-LOGIES

Conductive polymer-based graphene composites have garnered significant attention due to their outstanding electrical, mechanical, and thermal properties. These materials have been widely explored in advanced applications such as supercapacitors, sensors, electromagnetic interference (EMI) shielding, and next-generation electronic devices. In supercapacitors, the synergy between conductive polymers and graphene enhances charge storage capacity, cycle stability, and energy density. For sensors, the high conductivity and surface area improve sensitivity and response time, making them ideal for detecting gases, biomolecules, and environmental changes. Additionally, these composites serve as effective EMI shielding materials by absorbing and dissipating electromagnetic waves, protecting electronic devices from interference. The incorporation of graphene not only improves electrical conductivity but also enhances mechanical robustness and thermal stability, ensuring long-term reliability in demanding applications. These properties make conductive polymer-based graphene composites highly promising for cutting-edge technologies, driving advancements in energy storage, electronics, and multifunctional materials.

Table 2. Polymer selection for graphene-based composites

Polymer	Electrical Conductivity (S/m)	Mechanical Strength (MPa)	Thermal Stability (Decomposition Temp. °C)	Processing Methods	Common Applications
Polyaniline (PANI) (Zhang et al., 2010)	$\sim 10^{-4} - 10^0$	50 – 100	~250	In-situ polymerization, Solution casting	Sensors, supercapacitors, EMI shielding
Polypyrrole (PPy) (Lim et al., 2013)	$\sim 10^{-2} - 10^1$	20 – 80	~200	Electrochemical polymerization, Chemical vapor deposition (CVD)	Flexible electronics, energy storage
Polyvinylidene Fluoride (PVDF) (Samoei et al., 2024)	$\sim 10^{-10} - 10^{-8}$	40 – 60	~350	Solvent casting, Melt extrusion	Energy storage, EMI shielding
Polycarbonate (PC) (Wu et al., 2024)	$\sim 10^{-14} - 10^{-12}$	55 – 75	~300	Injection molding, Thermoforming	Structural applications, transparent coatings
Epoxy (Tang et al., 2013)	$\sim 10^{-15} - 10^{-12}$	70 – 120	~350	Solution casting, Resin curing	Aerospace, automotive, coatings

4.1 Supercapacitors

Supercapacitors require materials with high electrical conductivity, a large specific surface area, and excellent cycling stability. Conductive polymers such as PANI and PPy, when combined with graphene, improve charge storage efficiency, energy density, and capacitance retention (Liu et al., 2013). These composites provide high specific capacitance (>500 F/g) and long cycling life, making them suitable for energy storage systems.

4.2 Sensors

Conductive polymer-graphene composites exhibit excellent sensitivity and selectivity for chemical, gas, and biosensors (Priya et al., 2024). The high surface area and tunable conductivity enable rapid response times in detecting environmental pollutants, biomolecules, and gases like NO_2 and CO. Graphene-based sensors outperform traditional materials by offering ultralow detection limits and high reproducibility. Also, both graphene and graphene-based nanocomposites have been investigated as optical sensor materials (Jayatissa, 2023,. Samoei and Jayatissa, 2025).

4.3 Electromagnetic Interference (EMI) Shielding

With increasing demand for electronic devices, effective EMI shielding materials are essential to prevent signal interference and data loss. Graphene-polymer composites, particularly PVDF/rGO and PANI/Graphene, exhibit superior shielding effectiveness (>40 dB) across broadband frequency ranges, making them useful for aerospace, military, and telecommunications applications (Zahid et al., 2021).

4.4 Next-Generation Electronic Devices

Graphene-based conductive polymers enable flexible, lightweight, and high-performance electronic devices, including wearable sensors, transparent conductive films, and flexible displays. Their high conductivity (~10^3 S/m) and mechanical robustness allow the development of ultrathin, bendable circuits, contributing to the future of flexible and transparent electronics. Table 3 summarizes the primary applications of Gr/Polymer composites.

Conductive polymer-graphene composites hold immense potential for revolutionizing energy storage, sensing technologies, EMI shielding, and next-generation electronics. Their superior electrical conductivity, mechanical flexibility, and lightweight properties make them ideal candidates for futuristic applications. Ongoing research is focused on optimizing their performance, improving stability, durability, and large-scale processability, paving the way for widespread industrial adoption.

5. CASE STUDY: INTERACTION BETWEEN GRAPHENE AND PVDF

Graphene has good mechanical and electromechanical properties, however, the binding ability with polymers is limited to the weak Vander Waals forces, hydrophobic interactions, and the π-π interaction because of the homogenous sp^2 carbon composition. The interaction between π electrons in graphene and polymer molecules results in a robust interface. Polyvinylidene fluoride (PVDF) contains fluorine atoms that exhibit a strong affinity for carbon atoms. This affinity enables PVDF to bind effectively with graphene, facilitated by the presence of electron-rich benzene rings in graphene and electron-poor fluorine atoms in PVDF. The resulting polar ionic bond between carbon and fluorine atoms (C^+—F^-) contributes to the attractive interaction that holds the nanocomposite together. Moreover, functional groups present in graphene, such as hydroxyl or carboxyl groups, can engage in hydrogen bonding with the fluorine atoms in PVDF, further enhancing the adhesion between the two materials. PVDF serves as an excellent binder in the formation of conductive Gr/PVDF nanocomposites (Maharjan et al., 2023).

Graphene is a carbon allotrope with thermal and electrical properties frequently used as a filler in PVDF nanocomposites. Hydrogen-bond interactions between hydrogen-oxide groups on graphene's surface stabilize PVDF chains, causing the polymer's α to β phase transition. This is because strong charge biases attract each other, stabilizing the surface (Morita et al., 2022). Graphene-based filler materials are incorporated into a PVDF matrix through melt mixing, electrospinning, or solution casting to form Gr/PVDF nanocomposites.

Table 3. Applications of conductive polymer-graphene composites

Application	Key Performance Parameter	Typical Values of Parameter	Polymer-Graphene Composite Example	Potential Use Case
Supercapacitors	Specific Capacitance (F/g)	500 – 1200 (F/g)	PANI/Graphene, PPy/Graphene	Energy storage, Hybrid EVs (Shah et al., 2022, Moyseowicz et al., 2023).
Sensors	Sensitivity	~1 – 10^{-3} (ppm)	PPy/rGO, PEDOT-GO	Gas, biosensors, Environmental monitoring (Grigoroiu et al., 2023)
EMI Shielding	Shielding Effectiveness	40 – 70 (dB)	PVDF/rGO, PANI/Graphene	Aerospace, 5G, Military defense ((Anand and Pauline, 2021)
Next-Gen Electronics	Electrical Conductivity (S/m)	~10^2 – 10^3 (S/m)	PEDOT/Graphene, PPy-GO	Flexible circuits, Wearable devices (Moyseowicz et al., 2023, Maharjan and Jayatissa, 2022)

Gr/PVDF nanocomposite fabrication has resulted in homogeneously distributed nanolayers due to the functional group interaction between both nanomaterials. This observation can be attributed to the enhanced number of conductive paths for electron movement caused by heating (Chen et al., 2018). Al-Saygh et al. (2017) make a similar observation, noting that the composite's nanolayers come closer under pressure, reducing resistance (Al-Saygh et al., 2017). According to Adaval et al., (2022) the heterogenous polarization of the GO/PVDF nanocomposite is caused by interfacial interactions between difluoromethylene functional groups on the oxide's surface and molecular dipoles. GO has several functional groups, including hydroxyl and ketonic, which are essential in forming molecular interactions of polymer composites. GO's hydroxyl and carbonyl groups make electrostatic interactions with PVDF's fluorine groups by forming hydrogen bonds. This transforms the α phase into the β and γ phase (Zhang et al., 2020). The interaction between PVDF and graphene is shown in Fig. 1 as a schematic diagram.

Gr/PVDF nanocomposites have been used in many applications including such as piezoresistive pressures (Maharjan et al., 2022, Maharjan et al., 2023). In addition, it has been reported that the electrical properties can be optimized in post treatment in thermal annealing and IR light annealing (Samoei et al., 2023, Samoei et al., 2024). IR annealing can be effectively used to improve the bonding between polymer and graphene because IR light is absorbed by the graphene particles.
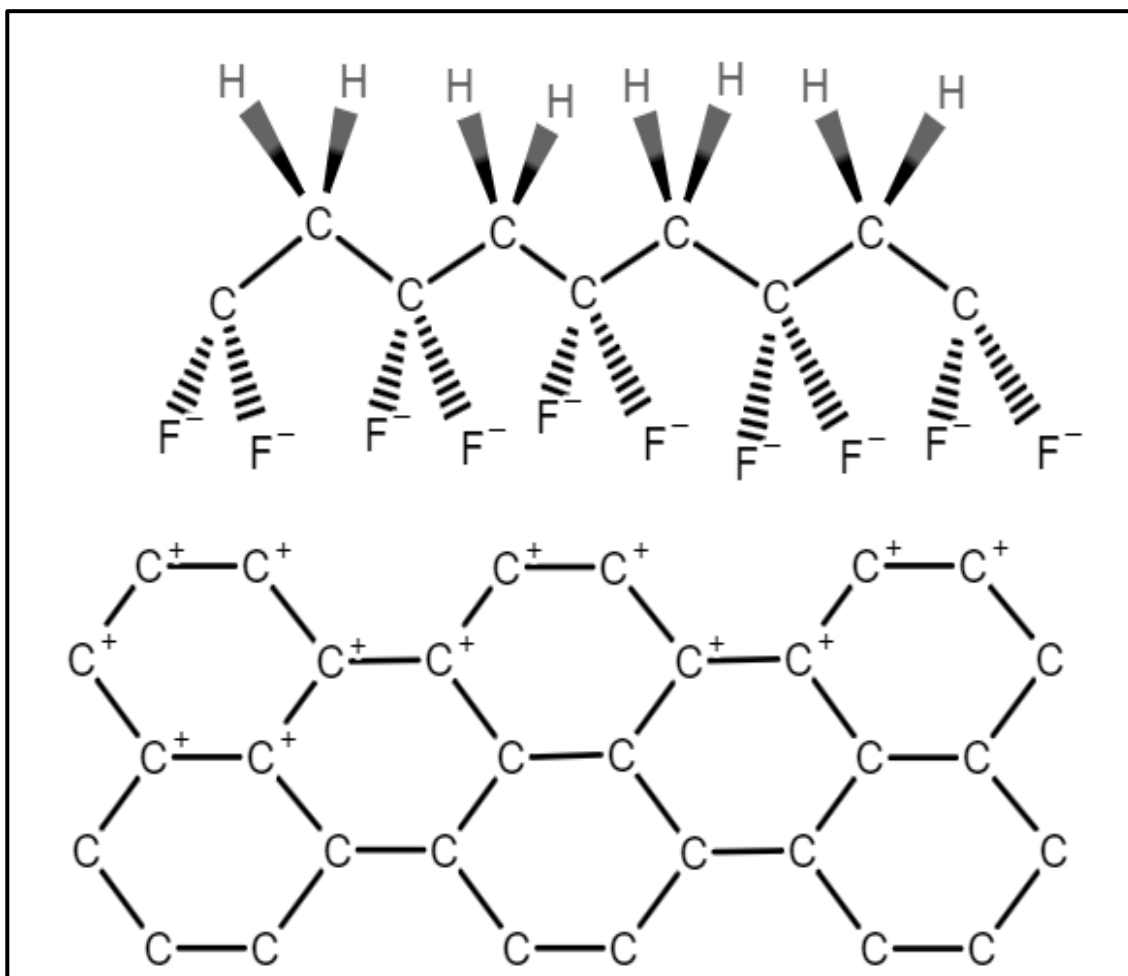

Fig. 1. Schematic diagram of the interaction between PVDF and graphene (Zhang et al., 2020)

6. CHALLENGES AND FUTURE PERSPECTIVES OF CONDUCTIVE POLYMER-GRAPHENE COMPOSITES

Despite the remarkable potential of conductive polymer-graphene composites in various applications, several challenges must be addressed to enable large-scale industrial adoption. These challenges primarily revolve around scalability, stability, and fabrication techniques. Overcoming these issues will require advancements in material processing, cost-effective synthesis methods, and enhanced structural stability for long-term performance.

6.1 Scalability Challenges

The large-scale production of conductive polymer-graphene composites remains a significant challenge due to the cost and complexity of graphene synthesis and dispersion. Traditional fabrication methods, such as chemical vapor deposition (CVD) and mechanical exfoliation, yield high-quality graphene but suffer from low throughput and high cost. Meanwhile, solution-based techniques, such as liquid-phase exfoliation (LPE) and chemical reduction, offer cost-effective alternatives but often result in structural defects and inconsistent material quality. Potential solutions for these technical issues are listed below:

- Scalable and green synthesis of graphene, such as electrochemical exfoliation and roll-to-roll CVD, can enhance production efficiency.
- Improved polymer processing techniques, such as melt blending and in-situ polymerization, can facilitate large-scale manufacturing while maintaining material properties.
- Advanced dispersion methods, including surfactant-assisted exfoliation and functionalized graphene sheets, can improve processability and uniformity in polymer matrices.

Primary stability concerns for conductive polymer–graphene composites in long-term applications include degradation due to environmental factors such as exposure to moisture, oxygen, UV light, and high temperatures. These factors can lead to the deterioration of both the polymer matrix and the graphene, reducing the material's electrical conductivity and mechanical properties. To improve their durability, strategies such as the incorporation of protective coatings, crosslinking of the polymer matrix, or the use of antioxidant additives can be employed to enhance the stability of the composite. Additionally, the use of graphene in its functionalized form can help improve the interaction between the graphene and polymer, further stabilizing the composite.

For large-scale industrial adoption of graphene-based polymer composites, future advancements in fabrication techniques and material optimization are essential. This includes the development of cost-effective, scalable production methods that ensure consistent dispersion of graphene within the polymer matrix, such as solution-based or melt-processing techniques. Additionally, optimizing the properties of the composites for specific applications, improving the compatibility between graphene and a broader range of polymers, and enhancing the reproducibility of the materials will be crucial. Advances in automation, quality control, and the creation of standardized production processes will help overcome barriers to large-scale production and make graphene-based composites more accessible and economically viable for industrial applications.

6.2 Stability and Long-Term Performance

A major concern in conductive polymer-graphene composites is stability, particularly in mechanical integrity, electrical performance, and environmental durability (Elenchezhian et al., 2021). Issues such as graphene aggregation, polymer degradation, and loss of electrical conductivity over time hinder long-term reliability in applications like energy storage, sensors, and EMI shielding. Potential solutions for these technical issues can be:

- Surface modification and functionalization of graphene can enhance its stability and improve interactions with polymer matrices.
- Cross-linking strategies and dopant engineering in polymers (e.g., PANI and PPy) can enhance structural integrity and electrical stability.
- Encapsulation techniques and protective coatings can prevent oxidation and degradation under harsh environmental conditions.

6.3 Fabrication Challenges and Optimization

The fabrication of graphene-polymer composites requires precise control over dispersion, polymer-graphene interaction, and processability to maintain uniform properties. Traditional methods, such as solution mixing and electrochemical deposition, often suffer from poor graphene dispersion, leading to phase separation and performance degradation. To overcome these limitations, advanced techniques like in-situ polymerization and surface functionalization of graphene have been explored to improve dispersion stability and interfacial bonding (Das et al., 2011, Wang et al., 2014). Potential solutions for these technical issues can be:

- Hybrid processing techniques, combining solution blending with advanced curing or crosslinking methods, can enhance uniformity.
- Additive manufacturing and 3D printing approaches provide new pathways for fabricating high-performance, customized conductive polymer-graphene composites.
- Plasma-assisted processing and laser-induced graphene synthesis offer novel techniques for fabricating conductive layers with superior interfacial properties.

7. FUTURE PERSPECTIVES

The large-scale industrial adoption of graphene-based polymer composites hinges on advancements in fabrication techniques and material optimization. Key challenges include achieving uniform graphene dispersion, scalable and cost-effective synthesis, and enhanced interfacial bonding between graphene and polymers. To address these challenges, several strategic developments are needed:

Integration with AI and Machine Learning: Computational methods can accelerate the discovery of optimal composite formulations by predicting material behaviors, optimizing processing conditions, and reducing experimental costs. AI-driven multi-scale modeling will enable precise control over composite properties for targeted applications.

Scalable and Cost-Effective Production: Advancements in high-yield, low-cost synthesis methods for graphene derivatives (e.g., graphene oxide, reduced graphene oxide) and their integration into common polymer processing techniques such as extrusion, injection molding, and solution casting will be crucial.

Advanced Dispersion and Interfacial Engineering: Ensuring uniform dispersion of graphene within polymer matrices through surface functionalization, solvent-assisted processing, or in situ polymerization will maximize electrical and mechanical performance. Enhanced interfacial adhesion using chemical modifications, compatibilizers, or hybrid nanofillers will further improve mechanical strength and durability.

Sustainable and Eco-Friendly Materials: The shift toward biodegradable and recyclable polymers, along with green synthesis methods for graphene, will promote environmental sustainability without compromising material performance.

Development of Multi-Functional Composites: The creation of smart materials with self-healing, shape-memory, and adaptive properties will unlock new frontiers in next-generation electronics, healthcare, and aerospace applications. These advanced functionalities will enhance the versatility of graphene-based polymer composites.

Automated and Scalable Manufacturing: Incorporating roll-to-roll printing, 3D printing, and high-throughput coating techniques will streamline mass production while ensuring material quality and performance consistency.

Standardization and Commercialization: Establishing industry-wide standards for material properties, synthesis protocols, and testing methodologies will bridge the gap between laboratory research and large-scale industrial deployment. Certification processes and regulatory frameworks will further accelerate commercialization.

By addressing these key areas, future advancements in fabrication techniques and material optimization will unlock the full potential of graphene-based polymer composites, driving their adoption in energy storage, flexible electronics, automotive, aerospace, and biomedical industries.

8. CONCLUSION

Conductive polymer-graphene composites have emerged as a promising class of materials that combine the high electrical conductivity of graphene with the mechanical flexibility and processability of polymers. This review explores the fundamental properties, fabrication techniques, applications, and challenges associated with these composites. Carbon-based nanomaterials, particularly graphene, enhance the electrical, thermal, and mechanical properties of polymer matrices, making them suitable for advanced technological applications. Various fabrication methods, including chemical vapor deposition (CVD), liquid-phase exfoliation (LPE), and reduction of graphene oxide (rGO), influence the quality and scalability of these materials. Polymer selection plays a crucial role in optimizing performance. These composites have demonstrated significant potential in applications such as supercapacitors, where they enhance energy storage efficiency, and sensors, where their tunable conductivity enables high sensitivity in biomedical and environmental monitoring. Additionally, they play a vital role in electromagnetic interference (EMI) shielding and next-generation electronic devices, including flexible displays, photonics and high-speed transistors. Despite their advantages, challenges related to large-scale production, material stability, and fabrication consistency must be addressed to enable industrial adoption. Future research should focus on optimizing synthesis techniques, improving material dispersion, and developing cost-effective processing methods to unlock the full potential of conductive polymer-graphene composites for commercial applications.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of this manuscript. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

Details of the AI usage are given below:

1. We checked the grammar of the manuscript ChatGPT.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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