**A Mini Review of Conductive Polymer/Graphene Composites**

**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 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.

1. **Introduction**

Carbon-based nanomaterials have gained significant attention in the development of polymer composites due to their ability to enhance thermal, electrical, and mechanical properties at relatively low concentrations [1]. These nanocomposites consist of a continuous polymer phase reinforced with carbon-based nanomaterials such as graphene, carbon nanotubes, and carbon fibers [2]. The addition of these nanoparticles modifies the composite’s properties based on their size, physical structure, and chemical interactions with the polymer matrix [3]. A critical factor in these materials' performance is the interfacial layer between the polymer and the nanoparticles, which dictates their structural and dynamic properties at the macroscopic scale [4]. Due to their large surface-to-volume ratio, nanoparticles serve as excellent fillers by increasing polymer-nanoparticle interactions [5]. However, in the case of graphene-based fillers, the strong van der Waals interactions can lead to agglomeration, which creates voids and weakens the composite by facilitating crack propagation [5,6].

Among carbon-based nanomaterials, graphene has emerged as a highly promising candidate for conductive polymer composites due to its exceptional electrical conductivity, mechanical strength, and chemical stability [6]. Graphene, a monolayer of sp²-hybridized carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits remarkable properties such as high intrinsic carrier mobility, superior thermal conductivity, and large surface area, making it ideal for a range of applications [7]. These include flexible electronics, supercapacitors, electromagnetic shielding, sensors, and biomedical devices [8]. However, to fully exploit graphene’s potential in polymer composites, challenges such as dispersion, interfacial compatibility, and processability must be addressed [9].

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 electrical and mechanical properties. Furthermore, key applications and challenges in the scalability of these composites are discussed, along with future perspectives on their industrial implementation.

**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) [10]. Table 1 below gives a summary of the fabrication methods of graphene and the general advantages and disadvantages of these processes.

**Table 1**: Summary of the fabrication methods of graphene [11-13]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **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** | CH4, C2H4, C3H8 gas/SiC | | Graphite | |
| **Processing Method** | 1. Epitaxial Growth | * *Annealing of SiC wafer* | 1. Mechanical exfoliation | * *Scotch tape* * *AFM tip* |
| 1. Chemical Vapor Deposition (CVD) | * *Thermal* * *Plasma* | 1. Chemical Synthesis | * *Reduction of GO* * *Sonication* |
| 1. Chemical Exfoliation | * *Exfoliation of GIC* |
| 1. 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 | |

1. **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) [14] and polypyrrole (PPy) [15] are favored for high electrical conductivity, while polyvinylidene fluoride (PVDF) [16] and polycarbonate (PC) [17] are chosen for their superior mechanical and thermal properties. Epoxy resins offer excellent adhesion and durability, making them suitable for structural applications [18]. Table 2 below provides a comparison of commonly used polymer matrices in graphene-based composites.

**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) [14] | ~10⁻⁴ – 10⁰ | 50 – 100 | ~250 | In-situ polymerization, Solution casting | Sensors, supercapacitors, EMI shielding |
| Polypyrrole (PPy) [15] | ~10⁻² – 10¹ | 20 – 80 | ~200 | Electrochemical polymerization, Chemical vapor deposition (CVD) | Flexible electronics, energy storage |
| Polyvinylidene Fluoride (PVDF) [16] | ~10⁻¹⁰ – 10⁻⁸ | 40 – 60 | ~350 | Solvent casting, Melt extrusion | Energy storage, EMI shielding |
| Polycarbonate (PC) [17] | ~10⁻¹⁴ – 10⁻¹² | 55 – 75 | ~300 | Injection molding, Thermoforming | Structural applications, transparent coatings |
| Epoxy [18] | ~10⁻¹⁵ – 10⁻¹² | 70 – 120 | ~350 | Solution casting, Resin curing | Aerospace, automotive, coatings |

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 [19, 20]. 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 [21,22].

1. **Applications of Conductive Polymers in Advanced Technologies**

Conductive polymer-based graphene composites have gained significant attention due to their exceptional electrical, mechanical, and thermal properties. These materials are widely utilized in various advanced applications, including supercapacitors, sensors, electromagnetic interference (EMI) shielding, and next-generation electronic devices. The incorporation of graphene enhances conductivity, mechanical strength, and overall stability, making these composites promising for cutting-edge technologies.

* 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 [23]. 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 [24]. The high surface area and tunable conductivity enable rapid response times in detecting environmental pollutants, biomolecules, and gases like NO₂ 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 [25,26].

**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 [27].

**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 (~10³ 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.

**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 |
| **Sensors** | Sensitivity | ~1 – 10⁻³  (ppm) | PPy/rGO, PEDOT-GO | Gas, biosensors, Environmental monitoring |
| **EMI Shielding** | Shielding Effectiveness | 40 – 70  (dB) | PVDF/rGO, PANI/Graphene | Aerospace, 5G, Military defense |
| **Next-Gen Electronics** | Electrical Conductivity (S/m) | ~10² – 10³ (S/m) | PEDOT/Graphene, PPy-GO | Flexible circuits, Wearable devices |

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.

1. **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 sp2 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 [28].

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 [29]. Graphene-based filler materials are incorporated into a PVDF matrix through melt mixing, electrospinning, or solution casting to form Gr/PVDF nanocomposites.

A diagram of a molecule

Description automatically generatedGr/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 [30]. Al-Saygh et al. (2017) make a similar observation, noting that the composite’s nanolayers come closer under pressure, reducing resistance [31]. According to Adaval et al. [31] 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 [33]. The interaction between PVDF and graphene is shown in Figure 1 as a schematic diagram.

Figure 1: Schematic diagram of the interaction between PVDF and graphene [34].

Gr/PVDF nanocomposites have been used in many applications including such as piezoresistive pressures [35,36]. In addition, it has been reported that the electrical properties can be optimized in post treatment in thermal annealing and IR light annealing [16,36]. IR annealing can be effectively used to improve the bonding between polymer and graphene because IR light is absorbed by the graphene particles.

1. **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.

**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. 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 [37]. 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.

1. **Future Perspectives**

Looking ahead, the optimization of conductive polymer-graphene composites for industrial applications will rely on several key advancements:

* Integration with AI and Machine Learning: Computational methods can accelerate the discovery of optimal composite formulations by predicting material behaviors and optimizing processing conditions.
* Sustainable and Eco-Friendly Materials: The shift towards biodegradable and recyclable polymers combined with green synthesis methods for graphene will ensure environmental sustainability.
* Multi-Functional Composites: The development of smart materials with self-healing, shape-memory, and adaptive properties will open new frontiers in next-generation electronics, healthcare, and aerospace applications.
* Standardization and Commercialization: Industry-wide standards for material properties, synthesis, and testing will be crucial in bridging the gap between laboratory research and large-scale industrial deployment.

1. **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.

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