

A Review Of Fabrication Methods, Production Techniques, And Applications Of Graphene

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In this work, the fabrication process, production process, and various applications of graphene and graphene-based materials are reviewed. Because of the excellent electrical, mechanical, and thermal performance, knowledge of the synthesis and application of graphene is required to enhance the industrial and scientific use of this material. The study thoroughly discusses various fabrication methods such as mechanical exfoliation, chemical vapor deposition (CVD), green processing, and chemical reduction, along with their efficiency, scalability, and applicability for certain applications. The review also compares the graphene-based composites production methods, structural modifications, and functional improvements of the composites. The authors' research indicates that the properties of graphene vary depending on its synthesis technique, and this affects its application in energy storage, electronics, biomedicine, and composites. Mechanical exfoliation yields high-quality graphene but with low scalability, whereas CVD yields high-purity graphene for electronic devices. Chemically synthesized graphene, though low-cost, usually requires further processing to improve performance. The review identifies the capability of graphene to transform diverse scientific and industrial applications: graphene-based materials are mechanically stronger, more electrically and thermally conductive, and highly relevant to next-generation technologies.

Keywords: Graphene; graphene composites; graphene-based materials; exfoliation; fabrication; chemical vapor deposition; applications.

1. Introduction

Graphene is a two-dimensional (2D) material with extraordinary electrical, thermal, and mechanical properties, making it attractive for a wide range of applications in many domains (Baig et al., 2021; Hu et al., 2018). Attention toward graphene has increased strongly because of its 2D, atomically thin honeycomb structure, in which carbon atoms are arranged through sp^2 hybridization. The excellent thermal, electrical, optical, and mechanical properties of graphene make it a prime material selection for multiple applications. Graphene demonstrates superior practical application potential because its monoatomic layer structure forms the thinnest strong carbon material among carbon family nanomaterials, including zero-dimensional fullerenes and one-dimensional carbon nanotubes (Liu et al., 2012; Peng et al., 2017).

Different derivative forms of graphene — including graphene, graphene oxide (GO), and reduced graphene oxide (rGO) — have been used to add necessary characteristics to produced

prototypes. The electrical properties of rGO surpass those of GO, but GO shows superior aqueous dispersion capability compared with rGO (Reina et al., 2017; Zhao et al., 2017). Composite materials combine either metal, ceramic, or polymer materials with graphene (Das & Prusty, 2013; Sun et al., 2020).

This review examines graphene fabrication processes together with production methods and implementation fields, especially for composite materials. It assesses fabrication methods from exfoliation to chemical vapor deposition, green methods, and chemical reduction regarding their production effectiveness, scalability, and material quality (Khan et al., 2017; Yang et al., 2012), and it evaluates production challenges, material cost efficiency, and functionalization problems (Yu et al., 2020). The main contributions of this study are as follows:

- A comprehensive examination of graphene synthesis approaches, covering both top-down and bottom-up methods, particularly exfoliation, CVD, and oxidation–reduction.
- A comparison of production methods in terms of graphene quality, scalability, and cost.
- A highlight of the integration of graphene with various composite materials, including polymers, metals, and ceramics, for boosting structural and functional properties of materials.
- A review of application domains — healthcare, electronics, energy storage, environment, and construction — together with the challenges and future directions for graphene commercialization.

2. Properties and Features of Graphene

Graphene consists of an individual carbon atom layer that forms a honeycomb lattice pattern through sp^2 hybridization. The material exhibits excellent mechanical properties, high electrical conductivity, excellent thermal properties, and optical transparency (Notarianni et al., 2016).

2.1 Structural Properties

The atomic arrangement of graphene produces distinctive features, including a thickness of 0.34 nm and an extremely large surface area of approximately 2630 m²/g (Yu et al., 2020). The production of graphene requires three main mechanisms — CVD, liquid-phase exfoliation, and direct chemical synthesis — each of which modifies its ultimate structural features (Yan et al., 2020).

2.2 Mechanical Properties

The mechanical properties of graphene are among the greatest of any material studied, with a tensile strength of ~ 130 GPa and Young's modulus of ~ 1 TPa (Lee et al., 2008; Zhang et al., 2014). The structural properties make it possible to create aerospace materials, biomedical implants, and various nanocomposites. The strength-to-weight ratio of metal alloys like Al–Cu–Li is enhanced by graphene, making them potential candidates for lightweight structural applications.

2.3 Electrical Properties

The ultrahigh electron mobility parameter (more than 200,000 cm²/V•s) of graphene, in conjunction with its excellent electrical conductivity, makes it suitable for creating next-

generation transistors, as well as flexible electronics and biosensors (Geim, 2009; Jariwala et al., 2012). With the zero-bandgap attribute, it allows for swift electron transfer, making the micro-supercapacitors and other energy storage devices more efficient.

2.4 Thermal Properties

Graphene has a thermal conductivity higher than 5000 W/m•K and can be used in the thermal management of electronic devices, high-performance battery applications, and heat dissipation coatings.

2.5 Optical Properties and Surface Functionalization

Transparent conductive films, as well as touchscreens and optoelectronic devices, are made using graphene because of its high optical transparency (about 97.7%) and electrical conductivity (Bae et al., 2010; Kobayashi et al., 2013). Functionalization strategies can further tailor the surface properties of graphene, thus enhancing its applicability in flexible sensors, wearable electronics, and biomedical diagnostics (Yan et al., 2011).

3. Fabrication Methods and Production Techniques

The production of graphene through molecular precursors begins with bottom-up techniques that implement epitaxial growth and CVD. The top-down category includes three main synthesis methods: LPE, mechanical exfoliation, and the oxidation–reduction method. Both LPE and the oxidation–reduction technique constitute prominent synthesis methods due to their scalable production combined with affordability under reasonable process standards (Anichini et al., 2018).

3.1 Mechanical Exfoliation

Mechanical exfoliation (the "scotch-tape" method) yields the best-quality, defect-free graphene monolayers, but the very low output of the process hinders any industrial application.

3.2 Chemical Vapor Deposition

CVD is essential for producing graphene as a 2D carbon material with highly desired electrical, mechanical, and thermal properties. In CVD synthesis, methane (CH₄) and hydrogen (H₂) hydrocarbon gases decompose at high temperatures (~1000 °C) to create a monolayer of graphene on metal catalysts, primarily copper or nickel. Single-layer graphene forms easily when using a copper catalyst because the metal has low carbon absorption properties. The doping of graphene happens through the addition of nitrogen or boron into the growth procedure, and the resulting material shows altered electronic characteristics. Raman spectroscopy and X-ray photoelectron spectroscopy provide methods for examining the structure, doping characteristics, and conductivity properties of synthesized graphene.

Grain boundaries in polycrystalline graphene form between merging graphene domains that possess different crystallographic alignment patterns during the growth process. These boundaries generate defects that take shape as pentagon–heptagon pairs, which act as charge carrier scattering points and reduce electrical conduction. Graphene is critical to industrial applications such as transparent conductive films and high-speed electronic devices, and control of the behavior of the grain boundaries is crucial.

3.3 Liquid-Phase Exfoliation

Liquid-phase exfoliation is a widely employed technique for the synthesis of graphene from graphite because of its good scalability and low cost. It includes the dispersion of graphite in a liquid and applying external forces to separate layers of graphene. There are two main techniques for LPE: high-shear exfoliation, which is based on shear forces induced by stirring to separate the layers of graphite into layers of graphene; and ultrasonic exfoliation, which uses bubbles to produce mechanical stress on the graphite, causing it to separate. Recent studies have focused on the use of ionic liquid crystals, green solvents, and Renewable polyphenol Surfactants like tea extracts and tannic acid for enhancing the sustainability of LPE.

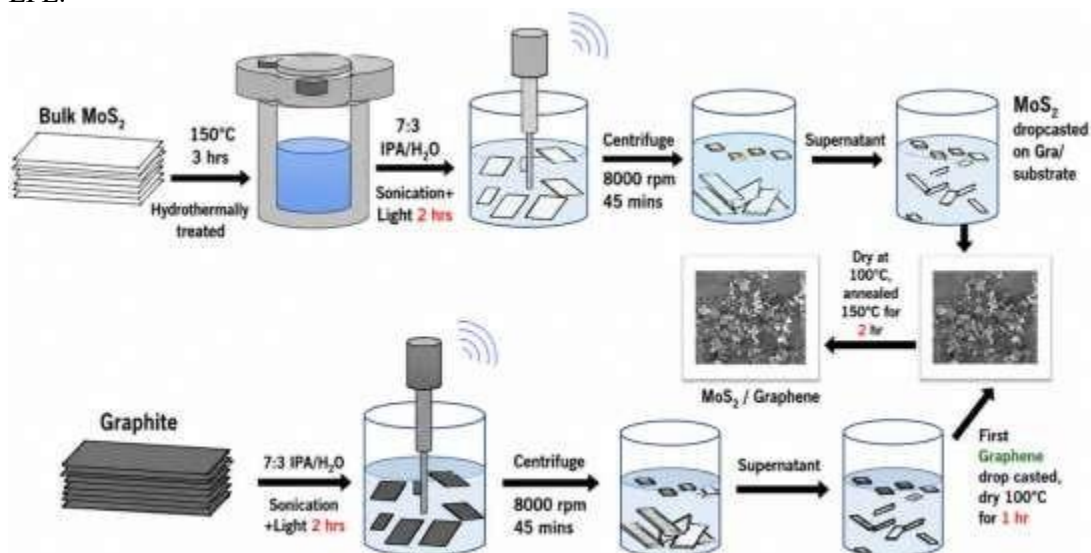


Figure 1. Liquid Phase Exfoliation

3.4 Electrochemical Exfoliation

Under the influence of an electric potential, the exfoliation of graphite, known as electrochemical exfoliation, is a good way to produce high-quality graphene. Traditional methods only exfoliate at the electrode/electrolyte interface, limiting conversion efficiency and scalability. The delocalized electrochemical exfoliation method has been developed for the production of graphene, which makes the exfoliation of dispersed particles of graphite with almost 100% yield possible and maintains the integrity of the structure of graphene. Electrochemically exfoliated graphene is a good candidate for applications in energy storage, electronics, and electromagnetic interference shielding due to its low defect density and high conductivity.

3.5 Chemical Oxidation-Reduction

Chemical reduction of graphene oxide is a cheap method that involves exfoliation of GO in aqueous solution, thin film growth, and subsequent chemical reduction of the material to graphene, the performance of which is typically further enhanced. Ordinary reduction methods

usually use toxic chemicals such as hydrazine and sodium borohydride, which are harmful to the environment. In response, researchers are developing eco-friendly reductions using plant extracts, UV-assisted reduction, and microwave heating. Plant extract-based reduction using ascorbic acid (vitamin C) shows great promise because it is both biodegradable and non-toxic; UV-assisted reduction eliminates oxygen functional groups without incorporating undesirable chemical residues, and microwave-assisted reduction allows fast deoxygenation with reduced use of toxic chemicals.

3.6 Green Synthesis from Biomass

Research on the synthesis of graphene using waste from agriculture has proved sustainable and low-cost methods (Das et al., 2017; Ismail et al., 2019). Biomass precursors such as rice husk, sugarcane leaves, tea waste, oil palm biomass, and chitin can be converted into graphene or graphene-like carbon through green routes (Debbarma et al., 2019), as illustrated in Figure 2. For example, a two-stage pyrolysis method has been studied for the production of GO from sugarcane dry leaves: in the first stage, pre-carbonization is achieved at 200 °C in an inert argon atmosphere with ferric citrate used as a catalyst, removing non-stable portions and volatile components while increasing the amount of carbon remaining in the material; the second stage involves heating the material to 800 °C, allowing structural transformation to graphene oxide, followed by post-treatment in sulfuric acid (H_2SO_4) to enhance oxidation and exfoliation. The obtained GO contains a purity of 3.35 C/O with rich oxygen functional groups, making it very suitable for catalysis, sensing, and energy storage applications. Similarly, tea waste has been converted to GO through a simple method with minimal production of toxic byproducts; oil palm biomass has been used as an anode material in energy storage devices, and chitin-derived graphene shows excellent properties for supercapacitor applications because of its high surface area and nitrogen doping.

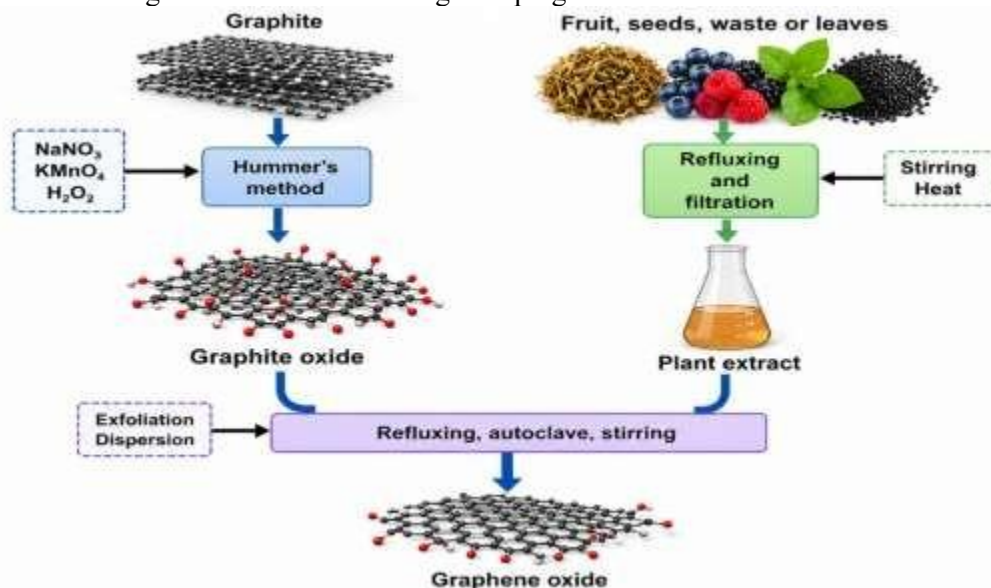


Figure 2. Green synthesis of reduced GO and bio-waste-derived graphene and their derivatives

The most important advantage of bio-waste-derived graphene is sustainability and flexibility, since different biomass sources can be utilized for synthesis. However, the quality and purity of the synthesized graphene vary because biomass composition varies, and the application of strong acids in post-treatment raises concerns regarding waste disposal and environmental impact.

3.7 Comparison of Fabrication Methods

Table 1. Comparison of graphene fabrication methods.

Property	Mechanical Exfoliation	Chemical Exfoliation / GO Reduction	Chemical Vapor Deposition
Quality of synthesized graphene	Best quality, no defects	More defects, lower quality	High quality, but varies
Maximum electron mobility	Up to 200,000 cm ² /V·s	~1,000 cm ² /V·s	Up to 100,000 cm ² /V·s
Feasibility for single-layer graphene	Possible but low yield	Possible but lower quality	Best for large-area single-layer graphene
Scalability	Not scalable	Scalable	Scalable
Maximum sample size	Small flakes (~100 μm)	Larger flakes, but limited	Large-area sheets
Production price	Very high	Moderate, cost-effective	High-tech, precise control
Production method complexity	Simple	Complex	High-tech and precise control

4. Graphene-Based Composites

Composites receive clear benefits from graphene incorporation in both structural and functional properties. Because of its high specific surface area, mechanical stiffness, and electrical and thermal conductivity, graphene acts as an ideal nanofiller for high-performance multifunctional polymer nanocomposites, improving strengthening and toughening, electrical conduction, and thermal transport (Khan et al., 2015). Even at very low loadings, graphene improves the mechanical properties of the composite matrix (Ibrahim et al., 2021). Graphene-based polymer composites are accordingly used in electronic devices, energy storage, sensors, electrostatic discharge and electromagnetic interference shielding, and biomedical applications.

Graphene also enhances metal and ceramic matrices. Research demonstrates that graphene–SiO₂ nanocomposites improve impact resistance and mechanical properties for structural applications, and graphene incorporation into metal alloys improves strength-to-weight ratios sufficient for lightweight structural applications. The fabrication route chosen for the

composite — solution mixing, melt blending, or in situ polymerization — determines the dispersion quality, interfacial bonding, and final property enhancement.

5. Applications

The applications of graphene span multiple industries, from biomedical engineering to energy storage and sustainable construction.

5.1 Healthcare and Biomedical Applications

Graphene and its derivatives have revolutionized the healthcare industry due to their applications in drug delivery, disease diagnosis, and treatment. The combination of exceptional attributes — high surface area, mechanical strength, electrical conductivity, and chemical stability — makes them suitable for biomedical innovation. With these functionalized GOs, the drug could be delivered with controlled distribution and generate a low level of adverse effects; therefore, functionalized GOs could be used as nanomaterials in drug delivery systems such as targeted drug delivery, which is successfully applied in chemotherapy, gene therapy, and delivery of neuroactive drugs. Graphene derivatives are also helpful for bioimaging and tissue engineering, such as detection of cancer cells using fluorescent graphene markers and the help of graphene-based structures in cellular development and correction of cell differentiation, which is important for tissue engineering and regenerative medicine (Shareena et al., 2018).

The graphene-based devices provide fast, accurate biomolecule detection with improved biosensing capabilities, such as glucose, DNA, haemoglobin, and cholesterol. The electrical characteristics of graphene make these biosensors more capable of transmitting signals, improving the sensitivity of the diagnosis compared to traditional methods (Janegitz et al., 2016). For instance, graphene coating on silica microfibers is able to identify DNA in its native environment, thus aiding precision medicine; graphene quantum dots with chemotherapeutic agents produce improved therapeutic outcomes. Electrochemical biosensing of both in vitro and in vivo has been widely demonstrated using graphene-based materials.

5.2 Electronics and Sensors

The electronics industry has been transformed by graphene owing to its remarkable electrical conductivity, flexibility, and durability. One of the major applications of graphene is in sensors, which can measure minute quantities of gas, detect changes in biomolecules, and monitor environmental changes with extreme accuracy – the medical diagnostics, air quality monitoring, and industrial automation industries are all heavily reliant on these thin, light sensors. High surface area combined with high conductivity leads to improved sensors that need to monitor the process in real time and improve sensitivity. For flexible electronic devices, health applications, and human-interface platforms, graphene is a key component of piezoresistive and capacitive sensors that sense mechanical deformations. The significant charge storage capacity and quick electronic movement in graphene also allow for the development of supercapacitors with increased capacity, higher energy density, and longer life.

5.3 Energy Storage

Graphene-based materials have potential for battery storage, supercapacitors, and electrochemical energy storage. Batteries featuring enhanced performance — faster charging, high energy reserves, and extended operational duration — result from graphene incorporation. Graphene supercapacitors facilitate fast charging and discharging, thus boosting the performance of EVs. Graphene also plays a central role in flexible lithium–sulfur and analogous alkali metal–chalcogen rechargeable batteries, where conductive graphene networks buffer volume changes and confine polysulfide dissolution (Peng et al., 2017).

5.4 Environmental Applications

Graphene-based nanomaterials demonstrate strong capability for water purification, including removal of dyes, heavy metals, and other organic pollutants through adsorption and membrane-based techniques (Khulbe & Matsuura, 2018; Perreault et al., 2015). Graphene-based sorbents have been developed for multipollutant removal in water (Yap et al., 2020), and graphene oxide membranes and graphene-coated filtration systems enhance separation efficiency. The combination of graphene-based photocatalysts, particularly TiO₂–graphene composites, has increased anti-fouling abilities while improving thermal discharge performance, enabling progress in renewable power generation and water decontamination technology.

5.5 Construction Industry

The construction industry now utilizes graphene as a leading revolutionary material that strongly enhances concrete properties (Liu et al., 2020). After its addition to concrete-based composites, graphene acts as a reinforcing agent that increases the material's capabilities in multiple construction applications. Studies have demonstrated that adding small amounts of GO or graphene nanoplatelets to cement-based materials increases compressive strength by 55% while tensile strength increases by more than 50% (Fakhim et al., 2014; Gong et al., 2014). Graphene oxide reinforcement of Portland cement paste improves mechanical performance through enhanced hydration and crack bridging. The nanoscale structure of graphene also works as a preventative measure against cracking, acting as a barrier that hinders the spread of cracks, which leads to longer-lasting concrete structures. The incorporation of graphene into concrete results in superior defense against both chloride and sulfate degradation, preventing chemical attacks on reinforced concrete infrastructure; infrastructure elements such as bridges, tunnels, and coastal buildings benefit from this property since they face challenging environmental conditions.

6. Challenges

6.1 Production Cost and Scalability

Graphene can be produced at the industrial scale, but it is challenging to obtain large-area, high-quality graphene, and most approaches have to make compromises between quality, cost, and throughput. While roll-to-roll (R2R) processes have proven their capability for producing large-area films, defect free transfer of film at an acceptable cost remains a challenge.

6.2 Functionalization Challenges

While the covalent approach is more effective in achieving durable functionalization between graphene and diverse materials, it results in the loss of part of the graphene conjugation system, which is detrimental to its intrinsic properties; the non-covalent approach is less harmful to the starting materials' properties but may lead to processing and stability issues. An important challenge in the design of graphene composites and devices is balancing the retention of the properties of graphene while simultaneously optimizing the interface engineering.

6.3 Environmental and Toxicological Impact

Environmental consequences and toxicological risks for humans need to be thoroughly assessed for large-scale production and application of graphene, with in vitro and in vivo studies reporting both low and high toxicity, depending on the physicochemical characteristics of the material (dose, lateral size, surface chemistry and functionalization) (Bianco, 2013; Fadeel et al., 2018; Lalwani et al., 2016).

6.4 Integration with Emerging Technologies

Studies on integrating graphene with emerging technology platforms — flexible electronics, sensing, bioelectronics, and next-generation information systems — are still maturing, and significant research is required before the full commercial potential of carbon nanomaterials is realized (Ferrari et al., 2014).

7. Future Work

7.1 Development of Scalable and Sustainable Production Methods

Future research should focus on large-scale, sustainable manufacturing practices for graphene through improvements in roll-to-roll processing and green synthesis methods to enhance commercial applications (Hong et al., 2021). Green graphene manufacturing through environmentally friendly exfoliation solvents and biomass-derived precursors lowers environmental impact while preserving the purity and performance characteristics of graphene materials.

7.2 Enhancing Structural and Electronic Properties

Methods for advanced characterization combined with defect engineering techniques need to be developed to produce graphene of high purity and tailored properties suitable for different applications.

7.3 Novel Functionalization Approaches and Safety Assessments

The research effort to develop advanced functionalization approaches through covalent and non-covalent methods can enable better use of graphene in flexible devices, energy storage systems, and biomedical devices. There are stringent tests that must be carried out to investigate not only the environmental effects of graphene production, but also its long-term compatibility as a medical application. Future studies also focus on the integration of graphene with advanced sensors and semiconducting technology for developing smart computing solutions, energy harvesting systems, and nanotechnological breakthroughs. The solution to

these research challenges can pave the way for the use of graphene in various industries and bring it from a research stage to commercialization.

8. Conclusion

To conclude, graphene is an amazing nanomaterial, which has attracted attention due to its mechanical, electrical, and thermal characteristics. This review highlights the key advances in the production of graphene, application frameworks, and production methods. Various synthesis methods — including mechanical and liquid-phase exfoliation, chemical vapor deposition, chemical oxidation–reduction, electrochemical exfoliation, and green biomass conversion — have been developed to create large-scale production of high-quality graphene products. The most prominent methods are liquid-phase exfoliation and CVD, which are scalable and have lower production costs, and mechanical exfoliation, which is the reference method for high-quality and defect-free samples for fundamental studies. Graphene-based materials are stronger than traditional materials, superior in electrical and thermal conductivity, and are of great interest in electronics, energy storage, biomedicine, environmental cleanup, and construction. Optimizing graphene and functionalization processes for large-scale, lower-cost graphene production is key to improving its performance in specific applications, as is the development of graphene fabrication methods and improving its market value as a next-generation technology.

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Declaration of interest

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement

MB conceived the study, performed the literature review and analysis, and wrote the paper.

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