Understanding Graphene Through Fabrication Routes, Distinctive Properties and Application Landscape

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Abstract: Graphene, a two-dimensional monolayer of *sp²*-hybridized carbon atoms arranged in a hexagonal lattice, has emerged as one of the most extensively studied materials due to its exceptional physicochemical properties. Its unique atomic structure gives rise to extraordinary electrical and thermal conductivity, high mechanical strength, large specific surface area, and chemical stability, positioning graphene as a versatile platform for advanced technological applications. This review provides a comprehensive overview of graphene, emphasizing the fundamental relationship between its structure and distinguishing properties. Major synthesis techniques, including mechanical exfoliation, chemical vapor deposition, liquid-phase exfoliation, chemical oxidation–reduction routes, and electrochemical exfoliation, are critically discussed with respect to material quality, scalability, and practical feasibility. Furthermore, the review highlights recent progress in a broad spectrum of graphene-based applications spanning electronics, sensing, energy storage and conversion, healthcare, water purification, protective coatings, and commercialization efforts. Current challenges related to large-scale production, defect control, and device integration are also addressed. Finally, emerging research directions and future prospects are outlined, underscoring the potential of graphene to transition from laboratory-scale research to widespread industrial implementation. This review aims to provide a consolidated perspective for researchers and engineers engaged in the development of next-generation graphene-based technologies.

Keywords: *Graphene, CVD, Mechanical Exfoliation, Epitaxial Growth on Silicon Carbide, Liquid-Phase Exfoliation, rGO, Electrochemically Exfoliated Graphene.*

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I. INTRODUCTION

Graphene occupies a foundational position in materials science, analogous to the transformative roles of artificial intelligence in software systems and quantum computing in information processing, with profound implications for future human–machine interfaces. Conceptually introduced by Boehm in 1988 [1] and formally defined by the International Union of Pure and Applied Chemistry (IUPAC) in 1977 [2], graphene is an exceptional two-dimensional carbon nanomaterial consisting of a single atomic layer of *sp²*-hybridized carbon atoms arranged in a hexagonal honeycomb lattice [3,4]. The stacking of individual graphene layers leads to the formation of graphite, characterized by an interlayer spacing of approximately 0.335 nm [5]. Within each graphene sheet, every carbon atom forms three strong in-plane σ bonds, while the remaining π electron occupies an orbital oriented perpendicular to the basal plane. The σ bonds generate a rigid, planar hexagonal framework that imparts outstanding mechanical stability, whereas the delocalized π orbitals govern interlayer coupling and play a central role in defining the electronic and physicochemical interactions between adjacent graphene layers.

Graphene exhibits a two-dimensional honeycomb lattice arising from the threefold planar coordination of carbon atoms, a structure that can be rigorously described within the single-particle Schrödinger framework. The lattice consists of two crystallographically inequivalent carbon atoms, commonly referred to as sublattices A and B, whose periodic repetition generates a hexagonal network. This arrangement may alternatively be viewed as two interpenetrating triangular sublattices, wherein each carbon atom is bonded exclusively to nearest neighbours belonging to the opposite sublattice. Monolayer graphene combines exceptional in-plane stiffness with relatively low resistance to shear deformation, a behaviour that originates from its distinctive bonding configuration. The strong in-plane σ bonds formed through sp^2 hybridization possess significantly higher bond energies ($\approx$615 kJ·mol^{-1}) than the sp^3 bonds present in diamond ($\approx$345 kJ·mol^{-1}), whereas the out-of-plane π bonds derived from 2p orbitals are comparatively weak. This pronounced contrast between σ and π bonding is responsible for the intrinsic mechanical anisotropy of graphene and its susceptibility to interlayer shear. The lattice constant of graphene is given by $a = \sqrt{3}a_0$, where $a_0 =$ 1.42Å corresponds to the nearest-neighbor carbon–carbon bond length [6]. Graphene must be clearly distinguished from ultrathin graphite, as its electronic properties are highly sensitive to the number of layers [7]. While single-layer and bilayer graphene exhibit zero band-gap behavior, few-layer graphene, typically comprising three to ten layers, shows partial overlap between the conduction and valence bands, resulting in semi metallic characteristics [8–10]. In Cartesian coordinates, the primitive lattice vectors of graphene can be expressed as $\mathbf{a}_1 = \frac{a}{2}(3, \sqrt{3})$and $\mathbf{a}_2 = \frac{a}{2}(3, -\sqrt{3})$, while the nearest-neighbor vectors are given by $\boldsymbol{\delta}_1 = \frac{a}{2}(1, \sqrt{3})$, $\boldsymbol{\delta}_2 = \frac{a}{2}(1, -\sqrt{3})$, and $\boldsymbol{\delta}_3 = \frac{a}{2}(-1, 0)$. The electronic band structure of graphene is governed by the symmetry of its hexagonal Brillouin zone, with the high-symmetry Γ, K, and M points playing a central role. In particular, the intersection of the conduction and valence bands at the K points gives rise to Dirac cones, producing a linear energy–momentum dispersion in the vicinity of the Fermi level. This unique dispersion relation underpins the massless Dirac fermion behavior of charge carriers in graphene and is responsible for many of its unconventional electronic properties.

II. PROPERTIES

- *Electronic Properties*

Since its isolation, graphene has attracted considerable attention owing to its extraordinary electronic characteristics. It exhibits a unique band structure in which the valence and conduction bands intersect at six inequivalent Dirac points within the Brillouin zone, resulting in an intrinsic zero band-gap nature. Charge carriers in graphene behave as massless Dirac fermions, leading to unconventional transport phenomena such as the anomalous integer quantum Hall effect and exceptionally high carrier mobility exceeding 2×10^5 cm^2·V^{-1}·s^{-1} at room temperature [11]. Graphene also supports ballistic charge transport over micrometre-scale distances and demonstrates extremely low electrical resistivity, approaching 10^{-8} Ω·m, surpassing many conventional metallic conductors [12]. These features establish graphene as a promising candidate for advanced electronic and optoelectronic devices.

- *Thermal Properties*

Graphene exhibits outstanding thermal transport performance. Early measurements on suspended monolayer graphene reported thermal conductivity values as high as ~5300 W·m^{-1}·K^{-1} [13].

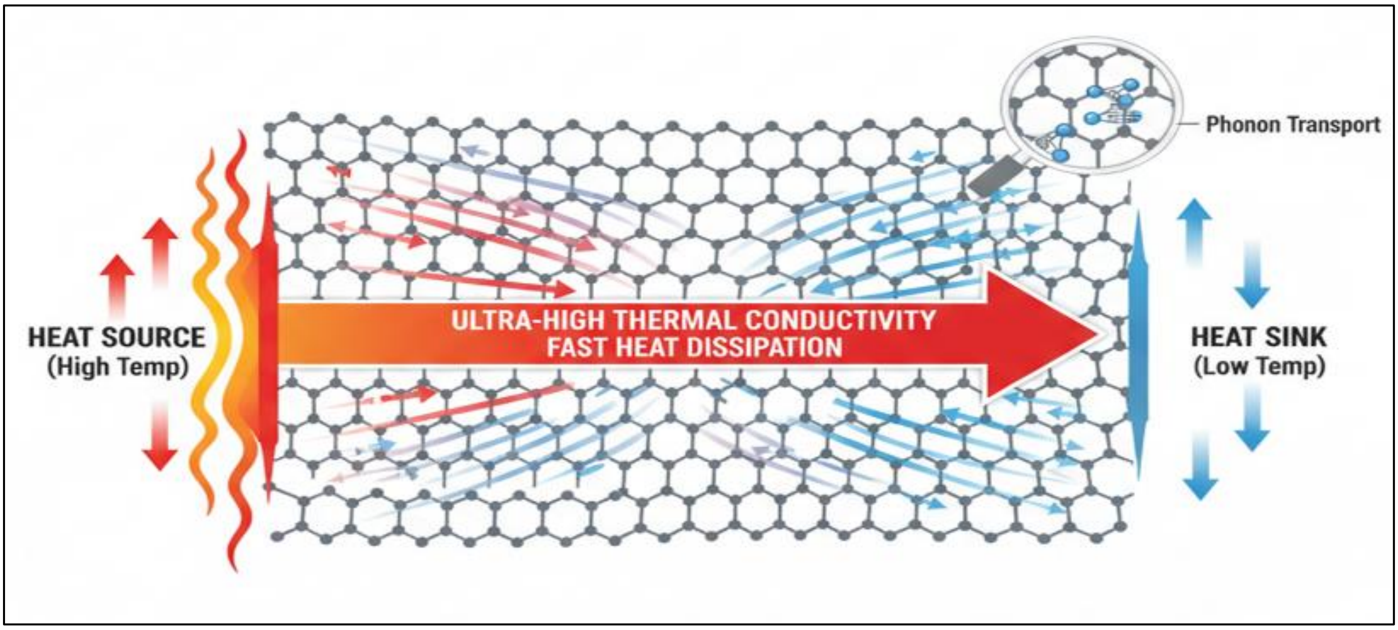

Fig 1 Schematic Representation of Graphene's Superior Thermal Conductivity and Fast Heat Dissipation

Although later studies revised these estimates, consistently reported values in the range of 1500–2500 W·m^{-1}·K^{-1} still position graphene among the most efficient thermal conductors known [14, 15]. This exceptional thermal conductivity underpins its growing relevance in thermal management applications, including heat spreaders and high-performance heat dissipation systems.

- *Optical Properties*

Monolayer graphene displays an optical absorption of approximately 2.3% across the visible spectrum while maintaining extremely low reflectance [16]. The optical absorption increases linearly with the number of graphene layers. When deposited on Si/SiO$_2$ substrates, optical interference effects significantly enhance its contrast, enabling straightforward identification of layer thickness via optical microscopy.

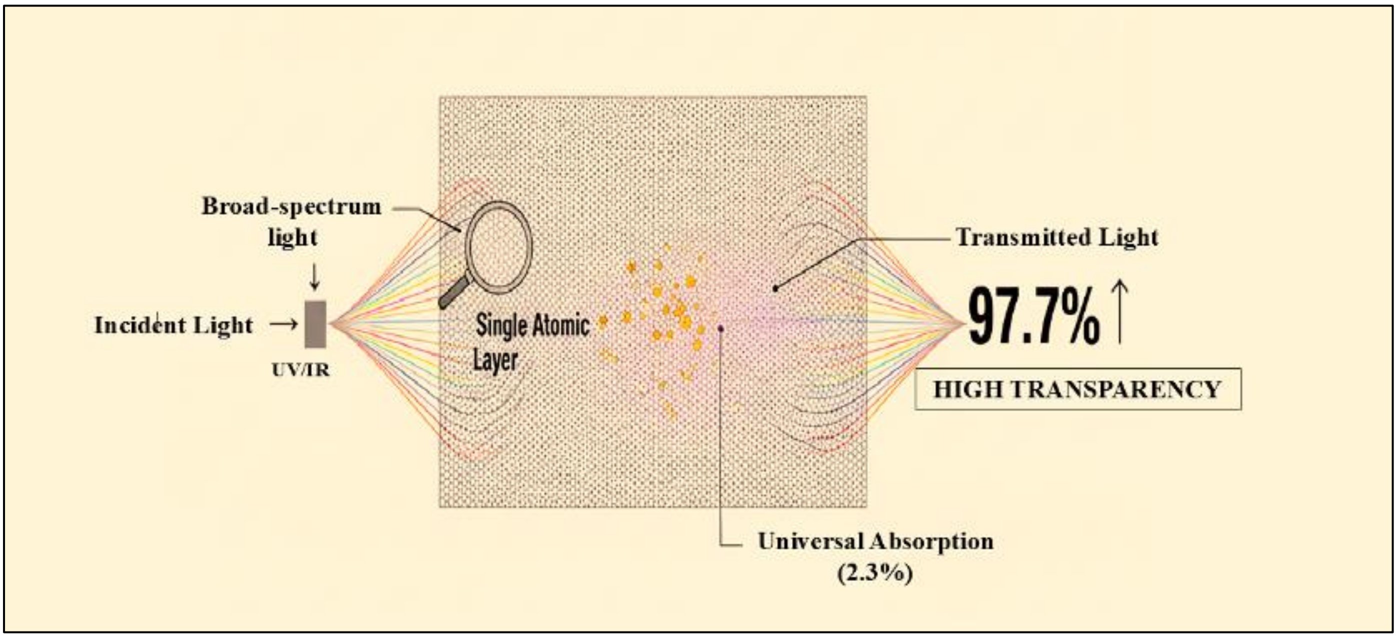

Fig 2 Illustration of Light Interaction with the Monolayer of Graphene

The unique combination of high optical transparency and excellent electrical conductivity makes graphene particularly attractive for applications in photonics and optoelectronics, including transparent electrodes, photodetectors, light-emitting devices, touch displays, photovoltaic cells, and terahertz-frequency technologies [17].

- *Mechanical Properties*

Graphene is one of the strongest materials known, exhibiting an intrinsic tensile strength of approximately 130 GPa and a Young's modulus close to 1 TPa, along with a fracture strain approaching 12% [18]. Raman spectroscopic studies under applied strain have shown that graphene can sustain tensile strains exceeding 1% and compressive strains up to ~0.7%, although the presence of structural defects significantly degrades its mechanical integrity [19]. Owing to these exceptional properties, graphene has been widely investigated as a reinforcing filler in polymer composites, where even low loadings (~0.1 wt%) can lead to substantial enhancements in stiffness and tensile strength.

- *Impermeability and Transport Properties*

Graphene has been experimentally demonstrated to be impermeable to all common gases, including helium and hydrogen, under ambient conditions due to the high energy barrier imposed by its dense π-electron cloud.

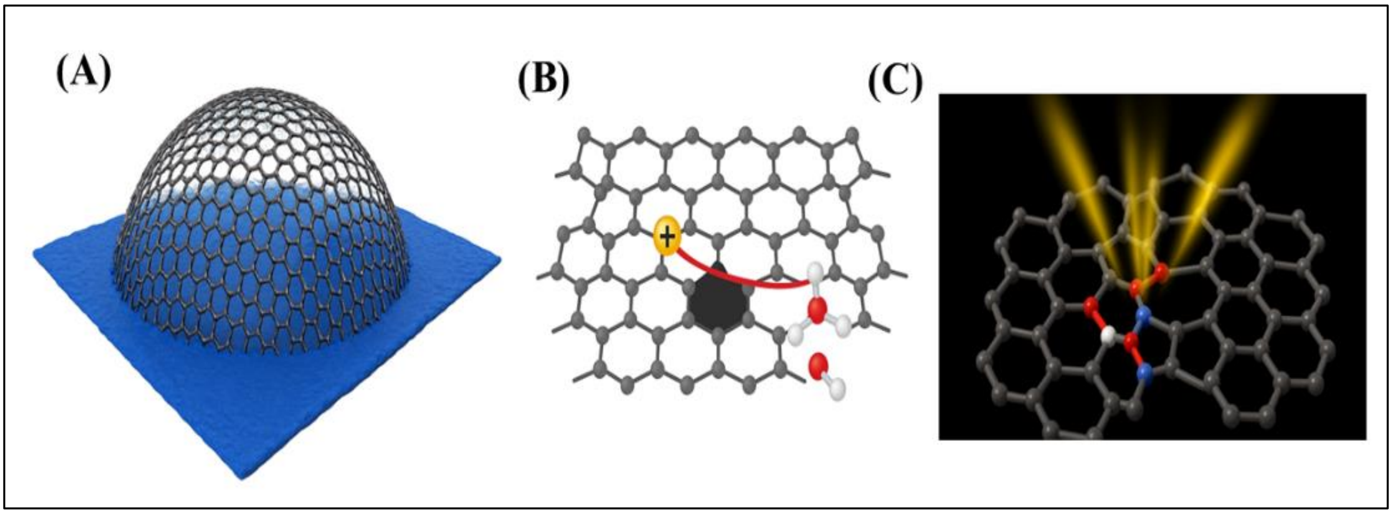

Fig 3 (A) Schematic Illustration of a Graphene Balloon, Highlighting its Exceptional Gas Barrier Property by Preventing Helium Permeation. (B) Schematic Representation Based on DFT Calculations, Demonstrating the Mechanism of Aqueous Proton Migration Through Intrinsic Atomic Defects in Graphene. (C) Illustration Depicting Thermal Proton Across a Graphene Sheet.

Interestingly, pristine monolayer graphene permits the transport of thermal protons, whereas AB-stacked bilayer graphene remains impermeable owing to its altered atomic configuration. In aqueous environments, proton transport may also occur through atomic-scale defects via the Grotthuss mechanism, highlighting graphene's unique selective transport behaviour [20].

- *Other Physicochemical Properties*

Graphene possesses an exceptionally high theoretical specific surface area of approximately 2630 $m^2 \cdot g^{-1}$ and a very high aspect ratio [21]. Surface studies have shown that graphene is generally hydrophobic, exhibiting a water contact angle significantly higher than that of graphite. Its surface energy under inert conditions indicates moderate interaction strength with gases. Furthermore, the adhesion energy of chemical vapor deposition–grown graphene on metal substrates is strongly substrate-dependent, reflecting variations in interfacial bonding and electronic interactions [22].

Table 1 Key Physical and Surface Characteristics of Monolayer Graphene (Thickness is Approx. 0.34nm)

Characteristics	Estimate
Carrier mobility	15000 cm^2/Vs
Electrical conductivity	Approx. 10^6 S/cm
Thermal stability	Approx. 2800 ˚C
Thermal conductivity	30005000 W/mK
Band gap	0 eV (zero bandgap)
Young’s modulus	1 TPa
Specific surface area	2630 m^2/g
Young’s Strength	130 GPa
Density	2.2 g/cm^3
Solubility	4.1 1.4 g/mL in DMF
	4.7 1.9 g/mL in NMP

III. ADVANCES IN GRAPHENE FABRICATION STRATEGIES

Early experimental isolation of graphene was achieved by Ruoff et al. through the mechanical exfoliation of graphite using adhesive tape, followed by dry transfer of the exfoliated layers onto silicon substrates—a procedure commonly known as the “Scotch tape” method [23]. Subsequently, Novoselov and co-workers successfully employed this technique to obtain high-quality monolayer graphene, thereby establishing its exceptional intrinsic properties [24]. Despite its effectiveness in producing defect-free graphene, the mechanical exfoliation method is inherently limited by low yield and poor scalability. Consequently, the large-scale synthesis of high-quality graphene remains a critical challenge for its widespread technological deployment. To address this limitation, substantial research efforts have been devoted to developing alternative synthesis strategies, which are broadly classified and discussed in the following sections.

- *Chemical Vapor Deposition (CVD)*

Chemical vapor deposition (CVD) is among the most established techniques for synthesizing graphene, particularly for applications requiring large-area, continuous, and uniform thin films [25]. Its compatibility with existing semiconductor manufacturing infrastructure makes it attractive for industrial-scale production.

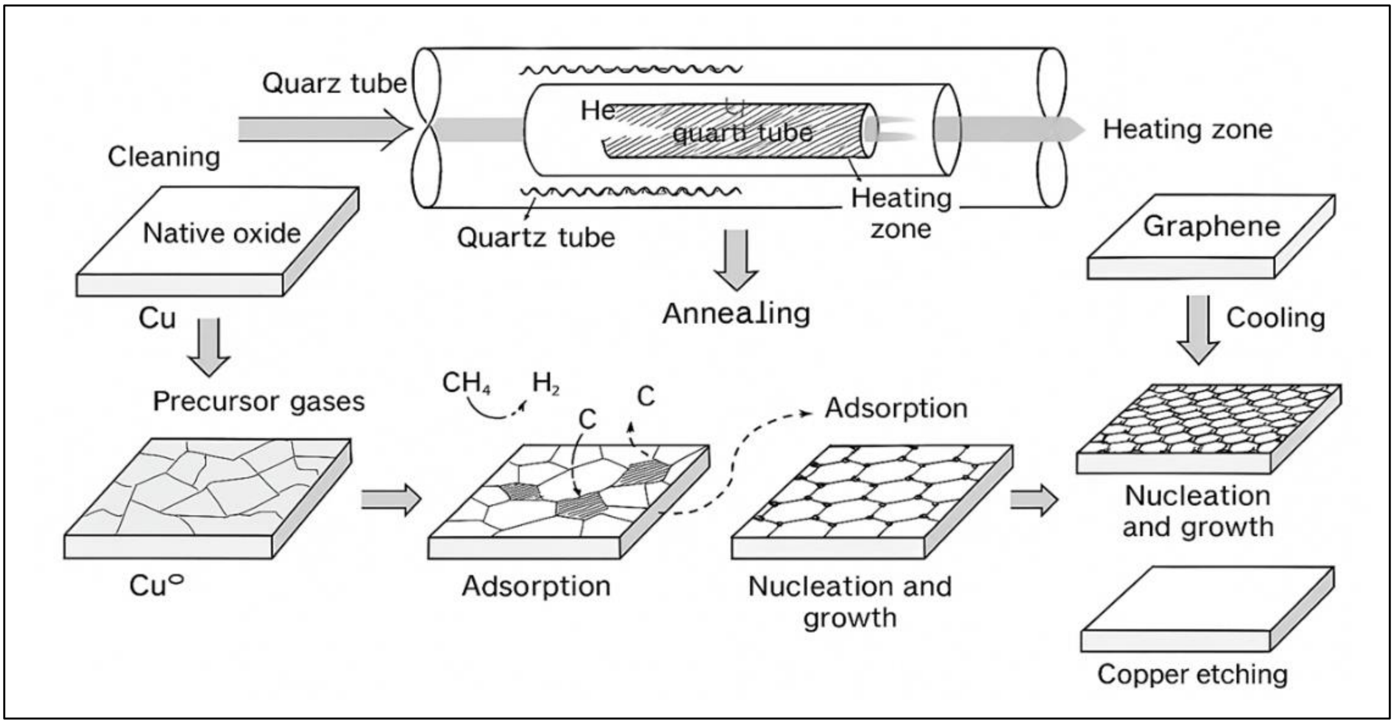

Fig 4 Schematic Illustration of Each Step of CVD Technique to Synthesize Graphene.

In a typical CVD process, hydrocarbon precursors such as methane or acetylene decompose on heated transition-metal substrates (e.g., Cu, Ni, Fe, or stainless steel) under carefully controlled temperature, pressure, and gas flow conditions. Graphene formation proceeds through precursor decomposition, carbon diffusion on or into the metal substrate, and subsequent surface assembly into a hexagonal lattice. Depending on the activation mechanism, CVD can be classified as thermal CVD or plasma-enhanced CVD (PECVD), the latter enabling graphene growth at reduced temperatures through plasma-assisted dissociation of carbon precursors. While CVD offers excellent control over film uniformity and thickness, high processing temperatures, vacuum requirements, and post-growth transfer steps remain key challenges.

- *Mechanical Exfoliation*

Mechanical exfoliation is the earliest technique developed for graphene synthesis and remains the reference method for obtaining graphene with the highest crystalline quality. The method relies on the weak van der Waals forces between adjacent graphite layers, which can be overcome through mechanical cleavage to isolate individual graphene sheets. When exfoliated onto Si/SiO_2 substrates, graphene layers can be readily identified due to optical interference effects [26].

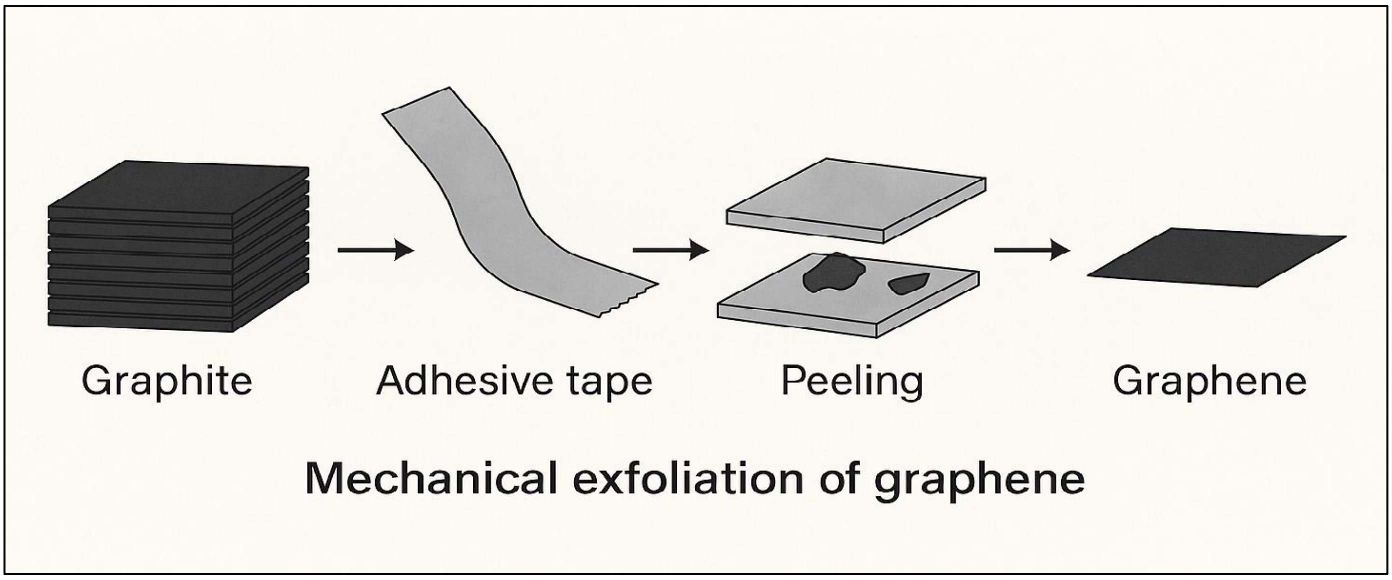

Fig 5 Stepwise Schematic Representation of Graphene Synthesis Via Mechanical Exfoliation.

Despite producing nearly defect-free graphene, mechanical exfoliation suffers from extremely low yield, poor reproducibility, and random flake size and thickness distributions. Consequently, its use is largely restricted to fundamental studies rather than scalable production.

- *Epitaxial Growth on Silicon Carbide*

Epitaxial growth on silicon carbide (SiC) involves the high-temperature thermal decomposition of SiC, typically above 1200 °C, during which silicon atoms preferentially sublimate from the surface, leaving behind carbon atoms that reorganize into graphene layers.

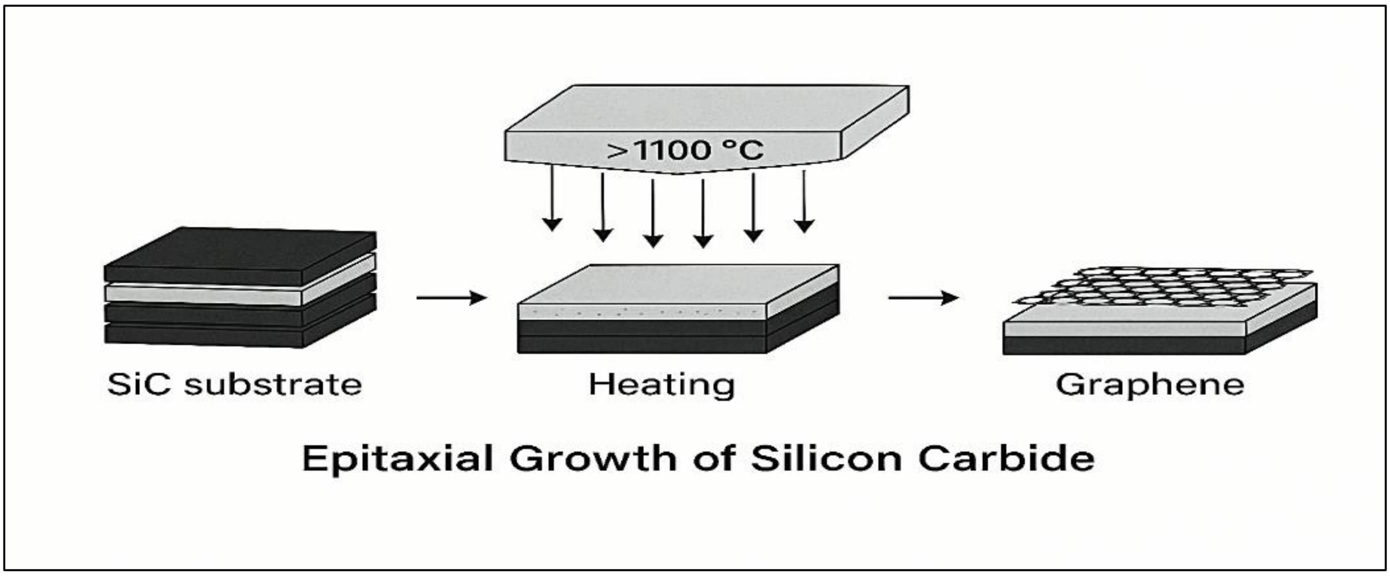

Fig 6 Schematic Representation of Epitaxial Graphene Formation on a Silicon Carbide (SiC) Substrate

The initial carbon layer formed, often referred to as the buffer or zero layer, is partially covalently bonded to the SiC substrate and does not exhibit the full electronic properties of freestanding graphene. Subsequent layers are weakly bound via van der Waals interactions and display graphene-like electronic behaviour. This method enables wafer-scale graphene growth without the need for transfer processes, making it suitable for high-frequency and high-speed electronic devices, although the high cost of SiC substrates and extreme processing conditions limit its widespread adoption [27].

➢ *Liquid-Phase Exfoliation*

Liquid-phase exfoliation has emerged as a scalable and high-throughput approach for producing graphene from graphite. In this method, mechanical energy supplied through ultrasonication or high-shear mixing overcomes the interlayer van der Waals interactions, resulting in the delamination of graphite into graphene sheets [28].

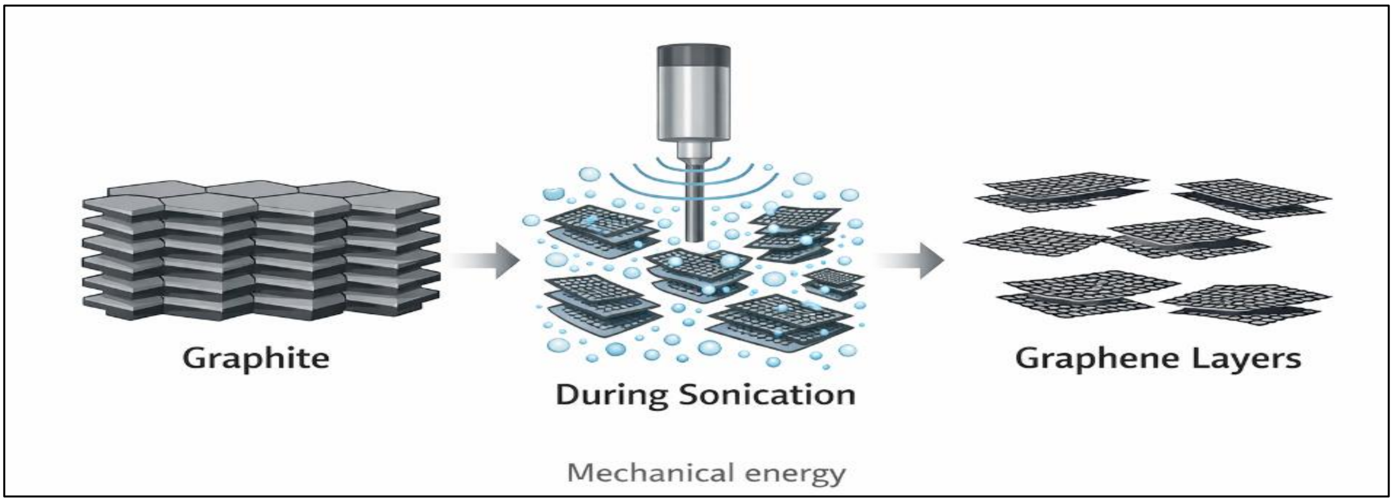

Fig 7 Schematic Representations of Graphene Exfoliation from Graphite Via Sonication

Under optimized conditions, this technique can yield large quantities of graphene at industrially relevant rates. Exfoliation efficiency can be further enhanced by chemical intercalation, where species such as ferric chloride, ammonium persulfate, or chromium trioxide expand the interlayer spacing prior to exfoliation. Although liquid-phase exfoliation is attractive for bulk production, it generally produces graphene with a broad distribution of flake sizes and layer numbers.

➢ *Chemically Reduced Graphene Oxide (rGO)*

Chemically reduced graphene oxide (rGO) is produced via the oxidation of graphite to graphene oxide (GO), followed by chemical or thermal reduction. Oxidative methods introduce oxygen-containing functional groups, including epoxy, hydroxyl, and carboxyl species, into the graphene lattice, rendering GO hydrophilic and easily dispersible. Subsequent reduction partially restores the sp^2 carbon network, improving electrical conductivity [29]. Various reducing agents and thermal treatments have been employed to tailor the degree of reduction and graphitization.

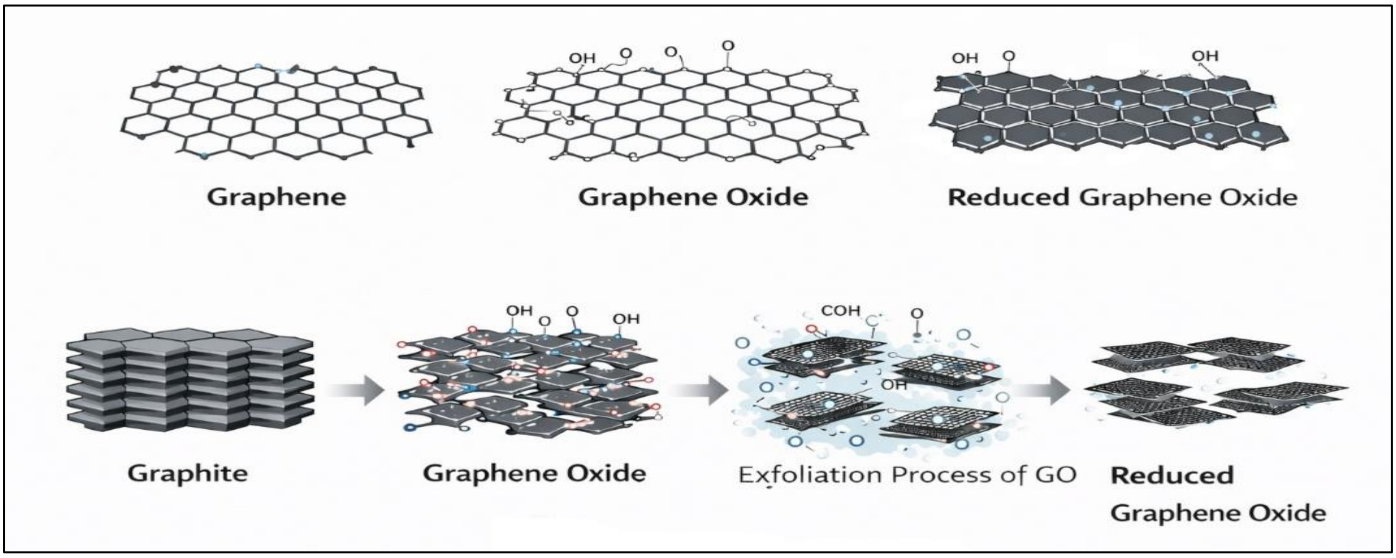

Fig 8 Schematic Diagrams of (a) Graphene, GO, and rGO Structures and (b) Their Synthesis from Graphite by Chemical Oxidation and Exfoliation.

While rGO can be produced at large scale and low cost, residual defects and incomplete removal of oxygen functionalities typically limit its electronic performance compared to pristine graphene.

➢ *Electrochemical Exfoliation of Graphene*

Electrochemical exfoliation has gained considerable attention as a scalable, cost-effective, and environmentally benign route for graphene synthesis. In this approach, graphite electrodes are subjected to a direct current bias in an electrolyte, leading to ion intercalation, gas evolution, and subsequent weakening of interlayer interactions. Exfoliation can proceed via anodic or cathodic mechanisms, depending on electrode polarity and electrolyte composition.

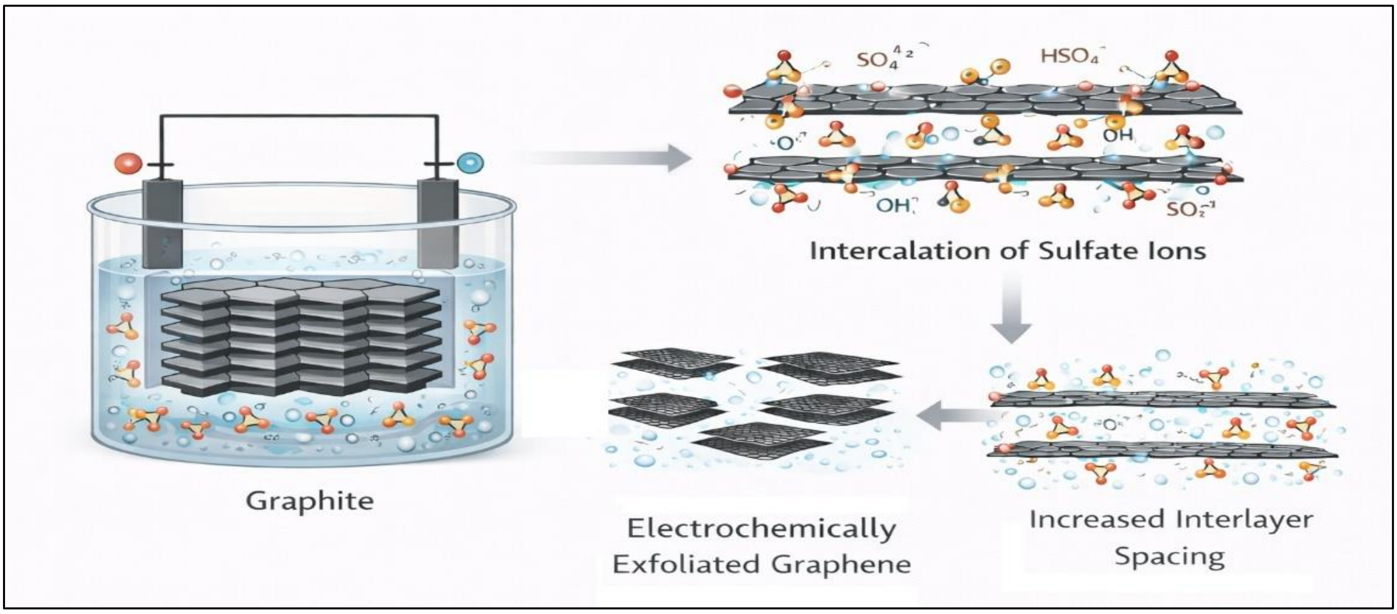

Fig 9 (a) Schematic Diagram of Electrochemical Exfoliation of Graphene

The choice of electrolyte critically influences exfoliation efficiency, defect density, and oxidation level. While acidic electrolytes such as sulfuric acid are effective, recent efforts have focused on milder inorganic salts and green, bio-derived electrolytes to minimize structural damage [30].

Graphene obtained via electrochemical exfoliation typically consists of few-layer sheets with micrometre-scale lateral dimensions, low oxygen content, and high electrical conductivity. Compared with CVD, mechanical exfoliation, and chemical reduction methods, electrochemical exfoliation offers a favourable balance between graphene quality, production rate, scalability, and environmental impact. Recent advancements have demonstrated that optimizing parameters such as electrolyte chemistry, applied voltage, electrode configuration, and operating temperature can significantly enhance exfoliation efficiency. This approach promotes efficient ion intercalation while suppressing excessive oxidation through the natural reducing action, enabling the eco-friendly synthesis of low-defect graphene.

IV. CURRENT AND PROSPECTIVE APPLICATIONS OF GRAPHENE

Graphene has garnered exceptional attention across scientific disciplines due to its unique combination of mechanical robustness, atomic-scale thickness, high electrical and thermal conductivity, and chemical stability. Following early efforts focused on scalable and economical synthesis, research has progressively shifted toward application-driven studies. Although only a limited number of graphene-based technologies have reached commercialization, continued advances in synthesis, characterization, and functionalization suggest that many emerging applications are approaching technological feasibility.

➢ *Biomedical and Healthcare Applications*

In biomedical science, graphene and its derivatives have attracted significant interest for both diagnostic and therapeutic applications. Their strong absorption in the near-infrared (NIR) region enables efficient photothermal conversion, making graphene-based materials particularly attractive for cancer therapy and neurological interventions. Functionalized graphene systems have demonstrated the ability to interact selectively with biomolecules, penetrate cellular membranes, and, in some cases, traverse the blood–brain barrier [31, 32]. These attributes have enabled applications in biosensing, targeted drug delivery, and neuroprotection. In the context of neurodegenerative disorders such as Alzheimer’s disease, graphene-based nanostructures have been shown to inhibit amyloid-β aggregation and promote disassembly of existing fibrils, effects that can be further enhanced under NIR irradiation while maintaining low cytotoxicity.

➢ *Chemical and Biological Sensing*

Graphene’s two-dimensional structure ensures that nearly all atoms are exposed to the surrounding environment, resulting in extraordinary sensitivity to chemical and biological species. Graphene-based gas sensors exhibit rapid response times, low detection limits, and high selectivity toward gases such as hydrogen, nitrogen dioxide, ammonia, and volatile organic compounds [33]. Sensor performance can be further improved through metal nanoparticle decoration, controlled defect introduction, or surface functionalization, which modulates charge transfer at the graphene–analyte interface. In biosensing applications, graphene field-effect transistors, electrochemical sensors, and fluorescence-based platforms have enabled ultrasensitive detection of proteins, nucleic acids, enzymes, pathogens, and biomarkers associated with cancer and cardiovascular diseases [34]. These characteristics position graphene as a key enabling material for next-generation diagnostic and point-of-care sensing technologies.

- *Energy Conversion and Storage Technologies*

Graphene has also found extensive application in energy-related technologies, particularly in photovoltaics, supercapacitors, and lithium-ion batteries. In photovoltaic devices, graphene serves as a transparent conductive electrode, charge transport layer, or catalytic component due to its high optical transmittance and electrical conductivity [35]. In dye-sensitized and hybrid solar cells, graphene-based electrodes have been shown to enhance charge collection efficiency and device stability. In energy storage systems, graphene's large surface area, excellent electrical conductivity, and mechanical flexibility make it ideal for high-performance supercapacitor electrodes. Graphene-based composites, especially those incorporating metal oxides or carbon nanotubes, exhibit enhanced capacitance, improved rate capability, and long-term cycling stability [36]. Similarly, graphene–silicon and graphene–carbon composites have demonstrated improved capacity retention and mechanical integrity in lithium-ion battery electrodes.

- *Water Purification and Environmental Applications*

Graphene-based membranes have emerged as promising candidates for water desalination and purification due to their high-water permeability and molecular-level selectivity. Nanoporous graphene and stacked graphene oxide membranes allow rapid water transport while effectively rejecting salts and contaminants [37]. Control over pore size, interlayer spacing, and surface chemistry enables tuneable filtration performance, offering advantages over conventional reverse osmosis membranes in terms of energy efficiency and flux. These properties make graphene-based membranes attractive for next-generation water treatment and environmental remediation technologies.

- *Protective and Functional Coatings*

Graphene's dense atomic structure renders it nearly impermeable to gases, making it an excellent barrier material for corrosion and oxidation protection. Graphene-coated metals exhibit significantly reduced corrosion rates and enhanced resistance to environmental degradation compared to uncoated substrates. In addition, graphene-reinforced composite coatings demonstrate substantial improvements in wear resistance, tribological performance, and mechanical durability [38]. The development of graphene-based superhydrophobic coatings has further expanded its utility, providing self-cleaning, antifouling, and anticorrosive surfaces suitable for harsh and marine environments.

V. TRANSLATION PROGRESS OF GRAPHENE FROM RESEARCH TO INDUSTRIAL DEPLOYMENT

The commercialization of graphene has progressed steadily in recent years, with a growing number of products transitioning from laboratory-scale research to real-world applications. This momentum is expected to intensify as manufacturing scalability improves and production costs continue to decline. Among the earliest adopters, the sports and consumer goods sectors have demonstrated notable success in integrating graphene into commercial products. Graphene-enhanced sporting equipment, including helmets, apparel, footwear, and tennis racquets, exploits the material's exceptional mechanical strength, thermal conductivity, and lightweight nature to improve performance and user comfort.

A prominent example is the introduction of graphene-coated motorcycle helmets, where graphene is applied as an external layer to enhance heat dissipation and thermal regulation, thereby increasing wearer comfort. In sports equipment, graphene incorporation has been shown to improve energy transfer, reduce weight, and enhance stability, leading to improved performance characteristics in tennis racquets and related gear. Similarly, graphene-infused footwear and textiles benefit from increased durability, thermal regulation, and antibacterial and antistatic properties. The integration of graphene fibers into fabrics enables heat retention and ultraviolet radiation shielding, further extending their functional value. Several industrial manufacturers have already launched or are actively developing graphene-enabled consumer products, highlighting the material's growing commercial viability. These early market successes underscore graphene's potential to bridge the gap between advanced materials research and large-scale industrial adoption, marking an important step toward its broader commercialization across diverse sectors.

VI. FUTURE OUTLOOK

The future development of graphene research is expected to transition from property exploration toward application-specific material design and system-level integration. As synthesis techniques continue to mature, emphasis will increasingly be placed on achieving precise control over layer number, defect density, surface chemistry, and lateral dimensions in a reproducible and scalable manner. In this context, environmentally benign and energy-efficient fabrication routes—particularly electrochemical and solution-based methods—are likely to gain prominence as viable alternatives to high-temperature or vacuum-dependent processes.

From an application perspective, graphene's role is anticipated to evolve toward multifunctional and hybrid architectures, where it is combined with polymers, metal oxides, semiconductors, or other two-dimensional materials to overcome limitations associated with pristine graphene. Such hybrid systems are expected to play a critical role in next-generation energy storage devices, flexible and wearable electronics, advanced sensing platforms, and high-performance protective coatings. In biomedical and environmental applications, future efforts will focus on improving long-term stability, biocompatibility, and selectivity through tailored functionalization strategies.

Standardization in graphene characterization, quality assessment, and reporting metrics will also be essential for accelerating industrial adoption and ensuring consistency across research and commercial products. Furthermore, advances in theoretical modeling and data-driven materials design are expected to provide deeper insight into structure–property–performance relationships, guiding rational optimization of graphene-based systems.

Overall, continued interdisciplinary collaboration among materials scientists, chemists, physicists, engineers, and industry stakeholders will be crucial for addressing existing challenges and unlocking graphene’s full technological potential. With sustained innovation and responsible manufacturing practices, graphene is well positioned to remain a key enabling material in the development of future advanced technologies.

VII. CONCLUSION

Graphene has firmly established itself as one of the most influential two-dimensional materials in contemporary materials science, owing to its unique atomic structure and the exceptional properties that arise from it. The single-atom-thick sp^2-bonded carbon lattice endows graphene with a rare combination of mechanical robustness, high electrical and thermal conductivity, chemical stability, and large accessible surface area. These intrinsic characteristics underpin its remarkable performance across a wide range of technological domains and distinguish graphene from conventional bulk and nanostructured materials.

This review has highlighted the close interdependence between graphene’s structure, properties, and synthesis routes. Considerable progress has been made in developing diverse fabrication strategies, including mechanical exfoliation, chemical vapor deposition, liquid-phase exfoliation, chemical oxidation–reduction routes, and electrochemical exfoliation. Each approach offers distinct advantages and limitations in terms of material quality, scalability, cost, and environmental impact. While mechanical and epitaxial methods remain essential for producing high-crystallinity graphene for fundamental studies, scalable techniques such as chemical vapor deposition and electrochemical exfoliation are increasingly driving industrial and application-oriented research. Continued optimization of synthesis parameters and electrolyte or catalyst design is expected to further improve yield, defect control, and reproducibility. The wide-ranging applications of graphene reviewed herein—from electronics, sensing, energy storage, and photovoltaics to healthcare, water purification, coatings, and composite materials—demonstrate its versatility as a multifunctional platform rather than a single-purpose material. In many of these fields, graphene has already shown clear performance advantages over traditional materials, while in others it plays a complementary role that enhances device efficiency, durability, or functionality. Importantly, several graphene-enabled technologies have progressed beyond laboratory-scale demonstrations, signalling a gradual transition toward practical deployment.

Despite these advances, challenges remain in achieving consistent large-scale production, precise control over defects and functionalization, and seamless integration into existing manufacturing processes. Addressing these issues will require coordinated efforts spanning materials synthesis, characterization, theoretical modelling, and device engineering. Future research is likely to focus on application-specific graphene architectures, hybrid and composite systems, and environmentally benign processing routes. With sustained interdisciplinary innovation, graphene is poised to continue evolving from a model two-dimensional material into a cornerstone of next-generation technologies.

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