

Green Routes for Graphene Production: A Comprehensive Review of Physical and Chemical Approaches

Dr. Manisha Bhutani

Associate Professor Bhagini Nivedita College, University of Delhi, Kair, New Delhi 110043

Graphene is a two-dimensional, one-atom thick sheet of carbon with carbon atoms arranged in a hexagonal lattice. It is an excellent conductor of electricity and heat, is very strong, and has a very large surface area. These favorable properties have led to research in energy storage, advanced electronics, biosensors, advanced coatings, and advanced composite materials. However, several environmental and economic barriers exist for using customary methods for synthesizing graphene, which typically involve organic solvents that are toxic in nature, and several energy-intensive processing steps. This Review seeks to present the latest developments in green production of graphene. Green production methods include green physical and green chemical approaches. Liquid phase exfoliation, mechanical and ball milling exfoliation, electrochemical exfoliation and plasma/laser-induced graphene preparation are dealt with in detail; their potential scale-up and reduced chemical consumption are highlighted for physical approaches. All methods encounter difficulties with product consistency and standardization. Green chemical reduction approaches that use plant-derived and biomolecule-based reducing agents have the advantage of being less toxic, but they have issues on large scales. Manufacturing challenges, including weaknesses in life cycle assessment and regulatory issues, are also reviewed; two major areas for the future, expected to accelerate scalable and sustainable graphene manufacturing, are hybridization of synthesis methods and the usage of artificial intelligence for manufacturing optimization.

Keywords: Graphene; Green Chemistry; Sustainable nanomaterials; Liquid phase exfoliation; Electrochemical exfoliation; Laser-induced graphene; Scalable graphene production.

1. Introduction

Graphene is a 2D carbon material consisting of a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Mechanically exfoliated graphene layers were first reported in 2004 (Novoselov et al., 2004). Since then, graphene has gained enormous interest in materials science owing to its excellent mechanical properties, electrical and thermal conductivity, and high specific surface area (Geim & Novoselov, 2007). These properties

make graphene suitable for many electronic and optoelectronic applications such as transistors, photodetectors, batteries and supercapacitors, sensors, solar cells, and composites (Novoselov et al., 2012). For example, the high electrical conductivity and high surface area of graphene have made it a promising material for use in supercapacitors, batteries and other energy storage devices, while its high strength and low weight have made it suitable for use in polymer and metal composites (El et al., 2016).

Aside from batteries and electronic devices, graphene and graphene-based materials are being studied for use in flexible electronics, advanced coatings, wearable sensors, water purification, biosensors, and medical diagnostic devices, each of which may benefit from the high physical and chemical performance and tunability of graphene. This increasing diversity of applications increases the demand for scalable and reliable routes to graphene synthesis (Song et al., 2021). Despite its promising versatility, the mass production of graphene came to be an issue. A collection of methods have been developed for producing graphene, including mechanical exfoliation, chemical oxidation-reduction, chemical vapor deposition, liquid phase exfoliation, electrochemical exfoliation and many more (Wang et al., 2019). These techniques are often energy-consuming and/or make use of toxic solvents and organic reagents which may cause issues with environmental sustainability during production. For example, solvents used for the liquid phase exfoliation process such as N-methyl-2-pyrrolidone, dimethylformamide and dimethyl sulfoxide are classified as environmentally hazardous materials (Fernandes et al., 2022).

Due to environmental considerations, green synthesis methods for graphene, focusing on minimally toxic precursor/solvent use, low-energy need and generally favorable environmental assessment, are desirable and needed while maintaining the use of high-quality and potentially easily up-scalable graphene material. As green nanomaterial research increases, the development of scalable and sustainable syntheses may promote commercialization and acceptance of the material as graphene (Zhang et al., 2018).

This review seeks to provide an overview of advances in green graphene synthesis. For the purpose of this review, green synthesis of graphene is based mainly on physical green synthesis of the material. Study describe the different methods of green synthesis: liquid based exfoliation, mechanical and ball-milling exfoliation, electrochemical exfoliation, and plasma or laser-induced synthesis. Finally, the current main issues with the industrial production of graphene are reviewed and potential pathways to a more eco-friendly production of graphene are suggested for future nanotechnology.

2. Literature Review

Since its isolation and characterization in 2004, scientific interest in graphene has exploded. Due to its superior electrical, thermal, mechanical, and surface properties, graphene is one of the most researched nanomaterials in contemporary materials science. Its properties have generated interest in possible applications in electronics, energy storage, sensors, and novel

composites, and a major area of research has thus been the development of efficient production methods.

Much of the initial research on graphene synthesis was concerned with techniques for producing graphene sheets in the lab. Mechanical exfoliation of graphene from graphite was among the first techniques developed, and remains a paradigmatic example of producing high quality (defect-free) graphene. The low yield and difficulty of scaling the process to a level useful in industry led to efforts to develop other methods of making larger quantities of graphene (Park & Ruoff, 2009).

These research efforts have led to multiple production methods of graphene, which differ according to their mechanism, cost, and scalability, and can be classified according to the mechanism of production of graphene structures from carbon sources. They have very diverse processing conditions and material qualities, but together they have greatly expanded the toolbox available for the production of graphene (Bonaccorso et al., 2012).

Many synthesis methods have been developed that can produce graphene with very high quality. However, due to either the high temperature, expensive equipment, or multi-step processing that can be used for synthesis, some methods may not be amenable to large-scale production. Recent efforts have thus been towards understanding the trade-off between scalability, quality, and efficiency.

In addition to engineering challenges, the environmental impact of conventional synthesis methods has spurred research into environmentally friendly synthesis methods. Recently, research has focused on the development of green synthesis methods that not only consider the scalability, structural quality, and performance of the produced graphene, but also minimize the environmental impact associated with graphene production. Several chemical green routes have been explored such as the reduction of graphene oxide to reduced graphene oxide (rGO) by using green reducing agents as opposed to toxic reducing agents such as hydrazine (Kurian, 2021). Synthetic graphene oxide is produced by chemical oxidation of graphite by the Hummers method and its modifications (Marcano et al., 2010).

Plants extracts are rich in green reducing agents in the form of biomolecules such as flavonoids, terpenoids and polyphenols that are capable of reducing graphene oxide with low toxicity (Perumal et al., 2022). The study details reductions of GO from *Vernonia amygdalina* leaf extracts in a mild hydrothermal route using phytochemical reducing and capping agents, which can be upscaled (Chufa et al., 2021). The leaf extracts of *Ziziphus spina-christi* have also been used to reduce GO to rGO with catalytic, anti-microbial and antioxidant activities (Mahmoud et al., 2022). More recent studies have also explored biomolecule-assisted and microorganism-mediated reduction approaches as a green strategy for the synthesis of graphene from GO (Dreyer et al., 2009). Alternative routes use biological molecules to ease the reduction of oxygen functional groups on GO in conditions that are at low toxicity and low temperature. Other processes rely on the use of carbon precursors extracted from biomass

whereby agricultural or biological waste is converted to graphene-based nanomaterials (GBNs) via environmentally-friendly practices in the frame of a circular economy (Zhu et al., 2010). Nonetheless, despite the green advantages and reduced environmental pollution and toxicity, there are still challenges regarding product purity, reaction control, and scalability, all of which are currently being researched (Zhong et al., 2015).

3. Green Chemistry Fundamentals of Graphene Production

Green chemistry is the design of chemical processes that consider environmental impact, reduce toxic chemicals, prevent waste and improve process efficiency during chemical manufacture without sacrificing product performance (Ogunseitan 2019). This has become a growing topic of interest in nanomaterial production as the rapid growth of nanotechnology has led to concerns surrounding the environmental sustainability and cost of nanomaterial production. In the specific case of graphene, green chemistry is defined as graphene production methods that minimize the ecological footprint without degrading graphene performance (Serrano-Lujan et al., 2019).

In contrast to bulk production methods, the manufacture of nanomaterials occurs on either an atomic or molecular scale, and minor changes to reaction conditions have been found to impact the quality and environmental impact of the product (Hochella et al., 2019). As a result, the principles of green chemistry are of particular interest in graphene synthesis routes, which can be evaluated against several criteria.

- **Energy efficiency:** The production methods for certain nanomaterials consume a lot of energy, contributing considerably to the overall environmental impact and the operating costs. Hence, reducing the energy required to produce green graphene has become a design priority.
- **Toxicity:** Some conventional methods of processing graphene use chemicals which could be harmful to humans and the environment. Research into safer alternatives mainly focuses on reducing toxic chemical use and harmful emissions during the production and use.
- **Cost and scalability:** To be a viable alternative to established methods, any environmentally friendly graphene production method must also be able to produce graphene in sufficiently high quantities and quality to meet demand. However, if scaling up the production process were not economically feasible, it is unlikely that this method would be widely adopted for industrial use, and a balance between these two factors must be found.

The sustainable development of nanomaterials can be supported by the concept of circular economy, seeking to minimize resource utilization and waste generation, and to maximize recovery and reintegration of materials throughout the production cycle (Gottardo et al., 2021). Life cycle assessment is one method to analyze the environmental impact of nanomaterials, from raw material extraction to end of life disposal. Both may be used to determine problem

areas in graphene synthesis or the development of more environmentally friendly synthesis methods and, together, form the basis upon which the green synthesis routes presented in this review have been appraised (Munuera et al., 2021).

4. Overview of Graphene Production Techniques

Synthesizing graphene is the fundamental first step toward its practical use in electronics, sensors, and advanced composite materials. Because graphene derives from carbon-based precursors such as graphite — which already has a layered structure similar to graphene sheets — various techniques have been developed to isolate or construct graphene structures. These techniques fall into two broad categories: top-down and bottom-up methods.

- **Top-down methods** separate graphene layers from bulk graphite through physical or chemical processes, such as mechanical exfoliation, liquid-phase exfoliation, chemical oxidation–reduction, and electrochemical exfoliation. These conventional top-down methods are generally considered more cost-effective and scalable for industrial production, but they can produce graphene with variations in quality and structure — such as structural defects and irregular layer thickness — depending on the exfoliation conditions. The degree of variation depends largely on the specific exfoliation method used and on post-processing conditions.
- **Bottom-up methods** build graphene from individual carbon atoms or molecular precursors such as methane or acetylene through chemical synthesis routes. Chemical vapor deposition, plasma-enhanced CVD, and epitaxial growth on silicon carbide substrates are common bottom-up approaches; CVD growth on copper foils, in particular, has become the dominant route to large-area, high-quality graphene films (Li et al., 2009). These techniques yield high-quality and uniform graphene, ideal for electronics and high-performance applications. They are, however, not as readily available, and they require elaborate and expensive equipment, energy input, and production costs, making them less scalable.

Both the top-down and bottom-up approaches do not meet both quality and environmental and economic responsibility in practice—the top-down approach compromises on structural consistency, and, on the other hand, the bottom-up approach compromises on environmental and economic responsibility (Serra-Llobet et al., 2016). This is the primary driving force behind the development of greener synthesis alternatives to minimize environmental impact while preserving quality and scalability (Julien et al.). Environmentally friendly exfoliation processes, mechanical exfoliation (which doesn't need any solvent) and alternative electrochemical systems are promising approaches.

5. Green Physical Routes for Graphene Production

Green physical synthesis routes have gained a lot of interest as alternative sustainable synthesis routes. The traditional synthesis sometimes involves issues of potential chemical hazards and environmental impact for large-scale production, so research has focused on methods that

reduce the amount of toxic chemicals used, while minimizing energy consumption and increasing the potential for scaling up. Methods that rely on physical means — rather than chemical oxidation and reduction reactions — are considered particularly promising.

The green chemistry benefits of the physical routes are that they can make graphene without using strong oxidizing agents, toxic solvents, or more than one step of chemical processes that create toxic byproducts. This shrinks the chemical footprint of production compared with conventional chemical routes. Several physical processes have been investigated as greener routes, and each is covered in turn below, with attention to its sustainability profile, scalability, and current limitations.

5.1 Liquid Phase Exfoliation

Liquid phase exfoliation is one of the most established top-down approaches to graphene synthesis and has received sustained attention as a scalable, lower-cost production route. Layered graphite is dispersed in a liquid medium and then subjected to external forces from sonication or high-shear mixing, which overcome the weak van der Waals forces holding the graphite layers together and produce few-layer graphene nanosheets in suspension (Coleman, 2009). LPE is an efficient and scalable method: it produces stable graphene suspensions that can be further processed into coatings, composites, and even printable electronics (Tkachev et al., 2021).

Conventional LPE relied on organic solvents such as NMP, DMF, and DMSO, whose surface energies are compatible with and facilitate graphene exfoliation. However, their high boiling points, toxicity, and difficulty of recovery during industrial-scale manufacturing present significant health and environmental concerns. Research has therefore focused on developing green solvents that assist exfoliation without the negative environmental impact. Environmentally benign options such as water-based dispersions, alcohol–water mixtures, biosurfactants, and biodegradable solvents have been assessed as sustainable alternatives (Hernández et al., 2008).

Green LPE processes can use aqueous surfactants or naturally occurring stabilizers to keep exfoliated graphene sheets dispersed and prevent re-aggregation, providing electrostatic stability comparable to that of conventional LPE solvents (Lotya et al., 2009). One study showed that plant-derived surfactants and compounds such as tannins can achieve yields comparable to traditional solvent-based systems while reducing environmental impact.

From a sustainability perspective, LPE has several advantages. It operates at moderate temperatures and does not require complex equipment, making it energetically and financially cheaper for industrial-scale production (Coleman, 2012). In addition, producing graphene in liquid suspensions enables direct integration into solution-based fabrication processes such as inkjet printing, coating, and polymer composite manufacturing.

However, there are some limitations to LPE. Exfoliated graphene sheets may have different dimensions and layer thickness depending on the conditions of the pick-up method and can be

structurally defective due to prolonged sonication or high-shear mixing, which may influence the electrical conductivity and other mechanical properties of the exfoliated graphene sheets. Another drawback of the single-layer graphene method is that the yield is not as high as compared to bottom-up methods. The current research is focusing on the optimization of green solvents, the optimization of the parameters of exfoliation, and the optimization of the stabilization strategies used during layer formation.

5.2 Mechanical and Ball Milling Exfoliation

With their solvent-free and low environmental impact, mechanical exfoliation processes, especially ball milling, have proven to be promising green physical methods. The method is that graphite is subjected to repeated impact and shearing forces, which are caused by the grinding agent, such as stainless-steel balls, in the rotating milling chamber. This mechanical force is applied continuously and causes the breakage of the van der Waals interaction force between the graphite layers, which helps with the exfoliation of the graphene nanosheets (Paton et al., 2014). It is classified as a top-down process and has been described as a particularly effective method for large-scale graphene production, as it is simple, scalable, and uses a cheap, readily available graphite feedstock (Yu et al., 2022).

The process is almost entirely mechanical in nature, without the use of chemical reagents, and therefore produces much less toxic waste than conventional synthesis processes (Jeon et al., 2012).

Exfoliation efficiency can be enhanced by introducing solid dispersants or intercalating agents that get between the layers of graphite and prevent re-aggregation during milling. The use of biomass-derived additives is a target of green mechanical exfoliation: natural compounds such as melamine can act as dispersants that facilitate the separation of graphene layers and stabilize the resulting nanosheets during milling (Green & Hersam, 2009), and bio-derived molecules such as riboflavin mononucleotide (vitamin B2) have likewise been used in an eco-friendly, mechanochemical approach to produce covalently functionalized, highly dispersible, low-defect graphene (Sayyar et al., 2022). Ball milling has also been studied for producing graphene directly from biomass precursors, which further highlights its green potential.

Ball milling has several advantages for graphene manufacturing. It can be scaled up easily using conventional milling equipment already common in powder processing industries, enabling continuous industrial production (Nair et al., 2022). Moreover, because no chemical reaction conditions or high-temperature reactors are needed, ball milling reduces operational costs and simplifies process design. However, the intense mechanical forces involved can introduce structural defects or produce graphene with variable layer thickness — a limitation it shares with liquid phase exfoliation. Therefore, optimization of the parameters, including rotational speed, rotational time, and ball-to-powder ratio, is one of the significant research fields to enhance the quality of graphene production under green conditions and high yield (Sumdani et al., 2021).

5.3 Electrochemical Exfoliation

Electrochemical exfoliation is one of the environmentally friendly, efficient methods for preparing graphene, and has become a simple one-step, non-toxic technique that is highly promising for mass production (Danial et al., 2021). In this approach, graphite is employed as an electrode immersed in an electrolyte solution, and an external potential difference is applied to promote the ions to intercalate between the graphene layers. This makes the van der Waals forces between the graphite layers weak and causes the layers to be easily separated into graphene nanosheets in the electrolyte medium (Parvez et al., 2014). The technique has garnered much interest due to its ability to generate few-layer graphene sheets larger than a few micrometres without the toxic chemicals typically used in other methods.

One of the major benefits is the versatility of the green electrolyte systems that can be adopted. Aqueous salt solutions like ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) and ammonium thiocyanate (NH_4SCN) can be used as an electrolyte medium, which can effectively insert inside graphite layers without being toxic to the environment. These salt-based electrolytes enable electrochemical reactions to take place at low voltage, resulting in fewer structural defects in the graphene sheet than electrochemical reaction processes. Another area of interest is their potential for use as environmentally friendly alternatives: Deep eutectic solvents are mixtures of hydrogen-bond donors and acceptors that, when combined, become ionic liquids with low toxicity, high conductivity, and a variety of viscosities, which are good for graphite intercalation and exfoliation and have reduced environmental impact compared to organic solvents.

Electrochemical exfoliation has several benefits in terms of scalability, purity, and energy efficiency. It is considered one of the most promising ways to produce graphene on a large scale, which has a simple operation and is low-toxicity to the environment (Li et al., 2022). It can also generate graphene dispersions quickly and under mild conditions, in contrast with bottom-up methods such as CVD, which require high temperatures, environmentally harmful chemicals, and vacuum settings, and is thus ideal for industrial-scale production, for example, in the production of inkjet-printable media, coatings, and polymer composites, without complex processes for recovering graphene. The method also allows for relatively high-purity graphene, as the exfoliation does not involve intensive oxidation and reduction steps, which could lead to the introduction of oxygen-containing functional groups (Parviz et al., 2016). Parameters that affect the quality of the structure and thickness of the graphene made, including voltage, electrolyte composition, the position of the graphite electrode (cathode versus anode), and post-processing conditions, all influence the intercalation and exfoliation of ions. Although electrochemical exfoliation has benefits, it has its drawbacks, including the stability of the electrolyte, degradation of electrodes, and process parameters that may reduce the yield and quality of the exfoliated material unless they are controlled (Abdelkader et al., 2015). A major

current research effort is geared towards finding electrolyte compositions and electrochemical cell designs that further enhance the efficiency and sustainability of this pathway.

5.4 Plasma and Laser-Induced Methods

Plasma-based synthesis and laser-induced graphene production are promising green physical routes because they rely on high-energy physical processes rather than chemical reagents, allowing graphene to be made rapidly with minimal solvent use. They are therefore investigated as alternatives to conventional methods that require oxidizing agents or complex chemicals (Huang et al., 2020).

Laser-induced graphene is produced when carbon-containing substrates are irradiated by a focused laser beam, which converts the substrate into porous graphene through photothermal reactions (Huang, 2019). The laser energy heats the substrate and triggers carbonization and graphitization reactions that reorganize the substrate's carbon atoms into graphene-like structures in very short processing times, making this technique significantly faster than many traditional synthesis methods (Lin et al., 2014); laser processing has likewise become a well-established route for converting carbon materials - including graphene oxide and other precursors - into functional graphene structures for energy storage and sensing devices (Zhao et al., 2021). A major advantage of LIG is its simplicity: a process called laser scribing can directly convert biomass-derived carbon precursors such as polyimide or lignin into graphene without needing catalysts, vacuum, or very high temperatures beyond that of the laser. Indeed, the conversion of abundant, renewable bio-based carbon sources into 'green' laser-induced graphene has emerged as a promising direction for sustainable electronics (Claro et al., 2022). The process is highly scalable and cost-effective, since graphene patterns can be built directly on flexible carbon substrates with minimal post-processing, enabling rapid, low-cost, maskless fabrication of devices such as sensors (Zhu et al., 2021). Another advantage is precision: by adjusting parameters such as laser wavelength, scanning speed, and laser fluence, researchers can directly influence the conversion process and determine the resulting morphology, electrical conductivity, and structural ordering of the laser-induced graphene (Ye et al., 2018).

Plasma-based synthesis is another green physical route. Plasma techniques generate highly reactive ionized gases that decompose carbon precursors to create radicals and free ions, which then undergo nucleation — combining together to form stable graphene. During decomposition, hydrogen ions are absorbed, which cleans amorphous carbon and impurities, and finally produces pure graphene — without solvents, catalysts, or very high temperatures (Ostrikov et al., 2013). The approach is scalable; a plasma spray approach has successfully exfoliated graphite to graphene on the sub-kilogram scale, with ~85% single-layer selectivity, production rates of 48 g/h and nearly no basal-plane defects, and without the use of any intercalants, chemicals, or solvent (Islam et al., 2021). One study also showed that plasma-

based processes can convert carbon feedstocks such as plant waste and stems into graphene oxide rapidly in argon plasma, with high efficiency.

Despite these advantages, challenges remain. Graphene produced by laser-based synthesis shows less consistency than CVD-produced graphene, which can affect electrical performance in certain applications if used as-is. For plasma methods, optimization of parameters such as gas temperature and chamber pressure is necessary to improve structural uniformity. Nevertheless, ongoing advances in laser technologies and plasma reactor design are steadily improving graphene quality while maintaining the "green" benefits of these approaches. With further optimization, they may become attractive candidates for future scalable and environmentally responsible graphene production.

6. Comparative Overview of Green Routes

Table 1. Comparative analysis of green graphene synthesis methods based on environmental liability and sustainability metrics.

Method	Key Principle	Chemical Toxicity	Energy Demand	Waste Generation	Environmental Liability
Liquid Phase Exfoliation	Sonication/shear forces in aqueous or bio-solvents	Low to moderate, depending on solvent choice	Moderate (sonication-intensive)	Low to moderate	Moderate (reduced vs. conventional solvents)
Mechanical/Ball Milling	Shear + impact exfoliation	Very low (solvent-free)	Moderate	Very low	Very low (solvent-free; minimal emissions)
Electrochemical Exfoliation	Ion intercalation by applied voltage	Low (aqueous salts, DES)	Low to moderate	Low	Low (benign electrolytes; mild conditions)
Laser-Induced Graphene	Photothermal conversion of carbon precursors	Very low (no solvents/reagents)	Low (localized energy input)	Very low	Very low (no solvents; minimal waste; localized energy input)

Plasma-Based Synthesis	Ionized gas decomposition of carbon	Very low	Moderate	Very low	Very low (no chemical reagents)
Green Chemical Reduction (plants/biomolecules)	Reduction of graphene oxide using bio-agents	Low (non-toxic reducers)	Low	Low	Low (bio-based alternatives vs. toxic reducing agents)
Biomass-Derived Graphene	Carbonization of renewable feedstocks	Very low	Moderate	Low	Very low (renewable feedstocks)

The comparison shows that physical methods such as electrochemical exfoliation and laser-induced graphene both exhibit relatively low energy requirements compared with conventional methods, limited chemical toxicity thanks to green solvents/reagents, and low waste production. Mechanical exfoliation reduces environmental impact even further by forgoing solvents entirely, though at the expense of a consistent graphene structure. Green chemical reduction routes, on the other hand, significantly reduce toxicity compared with conventional methods but are limited by scalability and process consistency. Overall, electrochemical exfoliation and laser-induced graphene offer the most balanced trade-off between environmental sustainability and industrial feasibility.

7. Challenges and Limitations

Despite advances in green synthesis routes, several challenges continue to hinder the commercialization of sustainable graphene production.

Scaling from lab to factory. Most green synthesis routes have been conceived and optimized in laboratory settings, but scaling them to industrial production introduces increased costs, reduced graphene quality, or inconsistent yields. Industrially synthesised graphene needs to meet very specific criteria for uniformity, purity, and allowable defect density. The technical and economic hurdles delay the extensive application of graphene in energy storage applications like supercapacitors, electronics, and composite materials.

Lack of standardization: Graphene manufactured by different methods could differ considerably in terms of physical characteristics like layer number, size, and defect density. The differences have a direct impact on practical performance and make it hard to compare between studies and to set consistent industrial specifications (Ferrari et al., 2014). Not having

a standardized classification also brings uncertainty to supply chains – in one case the supplier markets what they would call ‘graphene’ and in the other case a product with a distinctly different composition and quality (Wick et al., 2014). Reliable characterization, consequently, for quality control and mass production of graphene is needed, which requires improved characterization standards and accepted graphene definitions internationally.

Environmental stability and life-cycle assessment gaps. LCA has been widely used to evaluate the environmental impact of emerging materials such as graphene. However, most LCA studies are based on laboratory-scale processes or extrapolations rather than real industrial systems, so the environmental performance of large-scale graphene manufacturing remains uncertain. Studies suggest that energy consumption — particularly electricity use during synthesis and processing — can be a dominant contributor to the carbon footprint of graphene production (Arvidsson et al., 2014); correspondingly, the use of decarbonized electricity sources has been identified as one of the key strategies for reducing the environmental impacts of graphene-based materials (Beloïn-Saint-Pierre & Hirschier, 2021). Comprehensive LCA studies that incorporate process data, energy demands, waste generation, and post-production impacts are therefore required to properly assess the sustainability of different synthesis routes.

Regulatory and safety considerations. As graphene and other nanomaterials enter commercial markets, concerns have arisen about occupational exposure to hazardous chemicals used in synthesis, environmental release of unrecovered toxic reagents and by-products, and the long-term health effects of working with nanomaterials (Boyes et al., 2017). Because the field is young, regulatory frameworks and standardized guidelines for the safe production, handling, distribution, and disposal of graphene and other nanomaterials are not fully established. Combating these uncertainties is crucial for the responsible and sustainable development, and ultimate commercialization, of graphene technologies (Gong et al., 2016).

8. Future Research Directions and Conclusion

In view of the environmental constraints of the traditional synthesis techniques, the production of graphene in an environmentally friendly fashion has become an area of significant research in the field of nanomaterial engineering. The processes to produce graphene can be generally divided into two categories: top-down and bottom-up. There are different methods to produce graphene, broadly classified as top-down and bottom-up, with each having its own set of pros and cons regarding scalability, structural quality, and industrial feasibility. Top-down approaches like liquid phase exfoliation, mechanical milling, and electrochemical exfoliation have proven to be promising methods for scalable production, but are still challenged by the production of graphene with different layer thicknesses and structural quality. However, bottom-up methods (e.g., CVD) yield graphene of higher quality, but are more complex and

energy-intensive and, therefore, not economically feasible on a large scale. The challenges underscore the need for synthesis strategies that account for material quality, scaling, and environmental sustainability.

The quality–scalability trade-off that has been observed among the methods reviewed has stimulated research into hybrid synthesis methods. These can include mechanical exfoliation combined with more environmentally friendly chemical processes, or plasma-assisted processes, to enhance the yield, uniformity, and performance of graphene. In addition to synthesis hybridization, hybrid structures of graphene combined with other nanomaterials have shown measurable improvements in the electrical, thermal, and mechanical properties of graphene-based materials for applications such as sensors and energy storage devices.

The standardization and process-optimization challenges identified across the reviewed routes have also driven growing interest in artificial intelligence and machine learning as tools for graphene synthesis design. Machine-learning models trained on experimental datasets can identify non-obvious relationships between synthesis parameters and graphene output characteristics. Building on these capabilities, AI-driven frameworks can reduce the need for trial-and-error by identifying optimal synthesis conditions and simulating graphene growth behaviour across varying processing conditions (Butler et al., 2018). This has been demonstrated concretely: machine learning was used to optimize flash graphene synthesis by identifying the key process parameters governing material formation (Beckham et al., 2022).

For sustainable graphene to move from laboratory research to widespread industrial implementation and commercialization, stronger collaboration between researchers, industrialists, and regulatory bodies can be essential. Success depends on improving scalability, establishing standardized characterization protocols, and developing life-cycle assessment frameworks capable of evaluating environmental impacts throughout the production process. In addition, regulatory policies addressing safety, environmental protection, and sustainable manufacturing practices can play a critical role in enabling responsible adoption at industrial scale.

Green synthesis routes represent a promising pathway for sustainable nanomaterial manufacturing. The routes explored in this review — particularly electrochemical exfoliation, bio-assisted ball milling, and laser-induced graphene — are well positioned to contribute to this transition. Realizing graphene's full potential in nanotechnology and advanced materials science can ultimately depend on whether sustainability and scalability can be achieved together.

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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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