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GRAPHENE SYNTHESIS AND ITS IMPLICATIONS ON ELECTRICAL PROPERTIES: A COMPARATIVE STUDY

SÍNTESE DE GRAFENO E SUAS IMPLICAÇÕES NAS PROPRIEDADES ELÉTRICAS: UM ESTUDO COMPARATIVO

SÍNTESIS DEL GRAFENO Y SUS IMPLICACIONES EN LAS PROPIEDADES ELÉCTRICAS: UN ESTUDIO COMPARATIVO

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ABSTRACT

This study investigates the impact of graphene synthesis techniques such as chemical exfoliation, chemical vapor deposition (CVD) and liquid phase exfoliation (LPE) on electrical conductivity. The objective is to understand how variations in synthesis methods influence the morphology of graphene and, consequently, its electrical characteristics. Synthesis techniques are explored in detail to identify how each process affects the structure and electrical performance of graphene. The results indicate that chemical exfoliation introduces more defects into the graphene structure, potentially reducing its electrical conductivity, while the CVD method tends to produce graphene with greater uniformity and superior conductivity. LPE, on the other hand, offers a balance between quality and production efficiency, making it particularly promising for large-scale applications. The study provides valuable information for selecting synthesis methods based on specific graphene application requirements. The findings could facilitate the development of more efficient materials for advanced electronics, contributing to the optimization of industrial graphene production processes and promoting significant advances in materials technology.

Keywords: Graphene. Graphene Oxide. Graphene Film. Electrical Conductivity.

RESUMO

Este estudo investiga o impacto de técnicas de síntese de grafeno, como esfoliação química, deposição química de vapor (do inglês, Chemical Vapor Deposition CVD) e esfoliação em fase líquida (do inglês, Liquid Phase Exfoliation - LPE) na condutividade elétrica. O objetivo é compreender como variações nos métodos de síntese influenciam a morfologia do grafeno e, consequentemente, suas características elétricas. Técnicas de síntese são exploradas

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detalhadamente para identificar como cada processo afeta a estrutura e o desempenho elétrico do grafeno. Os resultados indicam que a esfoliação química introduz mais defeitos na estrutura do grafeno, reduzindo potencialmente sua condutividade elétrica. Enquanto o método CVD tende a produzir grafeno com maior uniformidade e condutividade superiores. Por outro lado, o LPE oferece um equilíbrio entre qualidade e eficiência de produção, tornando-o particularmente promissor para aplicações em larga escala. O estudo fornece informações valiosas para a seleção de métodos de síntese com base em requisitos específicos de aplicação de grafeno. As descobertas poderão facilitar o desenvolvimento de materiais mais eficientes para eletrônica avançada, contribuindo para otimização dos processos industriais de produção de grafeno e promovendo avanços significativos na tecnologia de materiais.

Palavras-chaves: Grafeno. Óxido de Grafeno. Filme de Grafeno. Condutividade Elétrica.

RESUMEN
Este estudio investiga el impacto de las técnicas de síntesis de grafeno, como la exfoliación química, la deposición química en fase vapor (CVD) y la exfoliación en fase líquida (LPE), sobre la conductividad eléctrica. El objetivo es comprender cómo las variaciones en los métodos de síntesis influyen en la morfología del grafeno y, en consecuencia, en sus características eléctricas. Se exploran en detalle las técnicas de síntesis para identificar cómo cada proceso afecta a la estructura y al rendimiento eléctrico del grafeno. Los resultados indican que la exfoliación química introduce más defectos en la estructura del grafeno, lo que puede reducir su conductividad eléctrica, mientras que el método CVD tiende a producir grafeno con mayor uniformidad y conductividad superior. Por otro lado, la LPE ofrece un equilibrio entre calidad y eficiencia de producción, lo que la hace especialmente prometedora para aplicaciones a gran escala. El estudio proporciona información valiosa para seleccionar métodos de síntesis basados en los requisitos específicos de aplicación del grafeno. Los resultados podrían facilitar el desarrollo de materiales más eficientes para la electrónica avanzada, contribuyendo a la optimización de los procesos industriales de producción de grafeno y promoviendo avances significativos en la tecnología de los materiales.

Palabras clave: Grafeno. Óxido de Grafeno. Película de Grafeno. Conductividad Eléctrica.

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1 INTRODUCTION

The process of obtaining graphene is a critical factor that directly influences its electrical properties and the viability of its application on an industrial scale (Neto *et al*., 2009). Since its isolation in 2004, graphene has attracted considerable attention due to its exceptional properties, such as high electron mobility, superior thermal conductivity, optical transparency, and remarkable mechanical strength (Novoselov *et al*., 2004; Geim & Novoselov, 2007). These characteristics make graphene a promising material for a wide range of technological applications, including nanoelectronics, energy storage, flexible devices, sensors, and advanced composites (Castro Neto *et al*., 2009). However, the performance of graphene in such applications is strongly dependent on the synthesis method employed, which determines not only its structural quality and layer thickness but also the presence of defects and impurities that can drastically alter its conductivity and overall behavior.

Methods such as chemical exfoliation, chemical vapor deposition (CVD), and liquid phase exfoliation (LPE) have been extensively studied to optimize the quality and characteristics of the produced graphene. Chemical exfoliation is a relatively simple and cost-effective route, enabling large-scale production, but it often introduces oxygen-containing functional groups and structural defects that compromise electrical conductivity (Boychuk *et al*., 2019). In contrast, CVD allows the controlled growth of high-quality graphene films with low defect density and superior electrical performance, though challenges remain in terms of process scalability, cost, and the transfer of films to suitable substrates (Vlassiouk *et al*., 2011; Cao *et al*., 2019). LPE, on the other hand, has emerged as an attractive alternative due to its scalability and ability to preserve the sp^2 carbon network more effectively than chemical oxidation methods, making it a viable option for applications where a balance between electrical performance and cost efficiency is required (Lotya *et al*., 2009; Xu *et al*., 2018). Each technique, therefore, presents specific advantages and limitations that affect the structure, purity, and consequently, the electrical properties of the final material (Li *et al*., 2009).

This article provides a comparative review of the most common 0methods of obtaining graphene, including chemical exfoliation, chemical vapor deposition (CVD), and liquid phase exfoliation, focusing on the relationship between synthesis techniques and the resulting electrical properties. Through the analysis of conductivity, resistance, resistivity, and other electrical metrics, we seek to establish a clear understanding of how different processes

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impact graphene's performance (Rezaei; Kamali; Kamali, 2020). Additionally, we discuss the measurement and characterization techniques that are crucial for assessing these properties, such as Raman spectroscopy, electron microscopy, and X-ray diffraction, which provide valuable insights into the quality, defect density, and morphology of graphene. The in-depth understanding gained from this study aims to provide guidelines for selecting suitable synthesis methods for specific graphene applications, as well as to promote the development of more efficient and economical manufacturing processes capable of meeting industrial demands.

1.1 MECHANICAL AND CHEMICAL EXFOLIATION

Mechanical and chemical exfoliation are two fundamental methods for obtaining graphene and graphene oxide from graphite (Stankovich *et al*., 2006). Each method has specific variations, such as the Brodie, Staudenmaier and Hummer methods, which mainly differ in the chemical reagents used and the subsequent treatment of the graphite.

The Brodie method, developed in 1859, was one of the first techniques for oxidizing graphite, using nitric acid and potassium chlorate. This method was less efficient compared to later developments, but it laid the groundwork for modern techniques of chemical exfoliation of graphite (Ikram & Jan, 2020).

Introduced by Hummer and Offeman in 1958, the Hummer Method is widely used due to its efficiency and relative safety. It uses a mixture of sulfuric acid, sodium nitrate, and potassium permanganate to oxidize the graphite. This method not only improved the efficiency of oxidation but also significantly reduced the risks associated with handling chemical reagents (Ikram & Jan, 2020).

Chemical methods, such as the Hummer method, tend to introduce more defects due to oxidation, while mechanical exfoliation can better preserve the structure of the graphene, although the distribution of sheet sizes may be less controllable. The detailed analysis by Casallas-Caicedo *et al*. (2019) on different exfoliation methods highlights the importance of selecting the appropriate method based on the desired final application of the graphene.

1.2 CHEMICAL VAPOR DEPOSITION (CVD)

Chemical Vapor Deposition (CVD) is one of the most effective methods for producing high-quality graphene on an industrial scale. Figure 1 illustrates the process of obtaining graphene by CVD. Hydrocarbon precursor gases enter the equipment and, in the internal

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chamber, are decomposed under heat. The resulting carbon atoms reorganize and deposit themselves on a heated metallic substrate (usually copper or nickel), catalyzing the formation of a graphene monolayer. The quality of graphene produced by CVD depends on several process parameters, including deposition temperature (Pedrazzetti, *et al*., 2017), system pressure and gas composition (Ta *et al*., 2017); (Cho *et al*., 2019), (Sirat *et al*., 2017), deposition time (Liu *et al*., 2011) and substrate.

Figure 1

Schematic diagram of the CVD system and growth mechanism of graphene on metallic substrate

Source: Yao *et al*., (2022).

Variations in CVD parameters have a significant impact on the electrical properties of graphene. The crystalline quality of graphene, which is strongly influenced by temperature and gas conditions, determines electron mobility, a key metric for electronic applications. Graphene with low levels of defects and atomic disorder exhibits superior electron mobility, which is crucial for high-performance electronic devices.

1.3 LIQUID PHASE EXFOLIATION (LPE)

Liquid Phase Exfoliation (LPE) is a versatile and promising method for the production of graphene, notable for its ability to produce large quantities of graphene efficiently and at relatively low cost. This method involves dispersing graphite in appropriate solvents to mechanically or chemically exfoliate the layers of graphene (Lotya, *et al*., 2009). The figure below illustrates the steps for obtaining graphene by exfoliation in the liquid phase. As illustrated in the ultrasonic exfoliation step (Figure 2).

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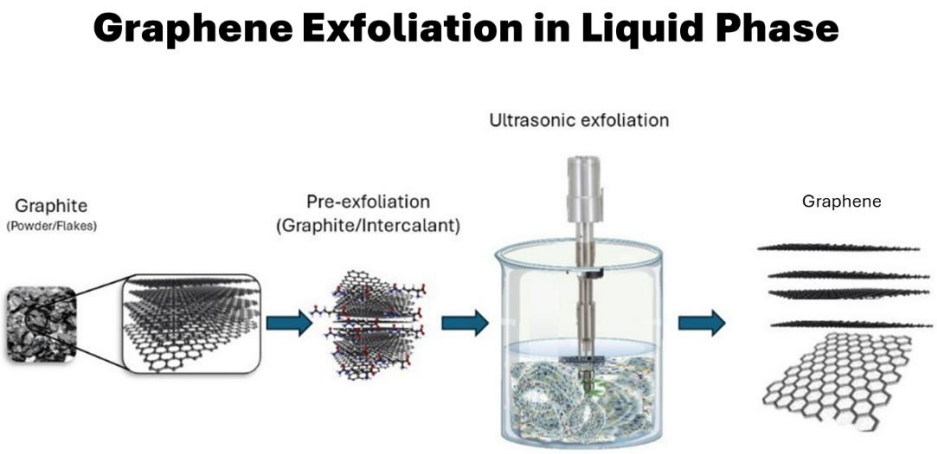
Figure 2

Stages of obtaining graphene in liquid phase

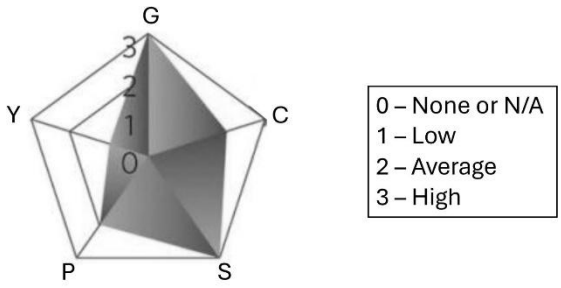


Source: Simao; Neves (2018).

The effectiveness of LPE in graphene production is significant, offering several advantages over other synthesis methods. In this sense, Figure 3 evaluates some of the general aspects of graphene obtained by exfoliation in the liquid phase, among these aspects were evaluated: in terms of graphene quality (G), cost aspect (C; a low value corresponds to high production cost), scalability (S), purity (P) and yield (Y) of the overall production process (Y) (Xu, *et al*., 2018).

Figure 3

Pentagonal radar plot of LPE method: quality (G), cost (C), scalability (S), purity (P) and yield (Y)



Source: Xu, et al. (2018).

The studies analyzed demonstrate that, although LPE offers a promising pathway for graphene production, the selection of suitable solvents and the optimization of processing conditions are essential to maximize the quality and yield of the produced graphene. These

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advancements continue to open new possibilities for the application of graphene in various fields, from electronics to advanced composites and new materials (Alaferdov *et al*., 2014; Li *et al*., 2020).

1.4 GRAPHENE STRUCTURE

The structure of graphene (monolayer) consists of a single plane of carbon atoms positioned at the vertices of hexagons. Each atom forms covalent bonds with three other atoms, sharing three of the four electrons from their 2s and 2p orbitals. These bonds are extremely robust, giving graphene remarkable structural stability. The fourth electron of each atom can occupy positions above or below the plane, allowing for great mobility in two dimensions. These free electrons have the ability to conduct heat and electricity (Hashimoto *et al*., 2004).

a) The method used to obtain graphene can influence the generation of defects in its structure and, consequently, its electrical, optical, thermal, and mechanical properties (Hernandez et al., 2008), as the method of graphene production affects the final sp^2 structure. To achieve better properties, graphene needs to be obtained in one or few layers. However, conventional methods for obtaining graphene inevitably introduce defects in its structure.

b) Some of these defects are 'intrinsic' ripples with dimensions between 8-10 nm laterally and 0.7-1.0 nm in height on the graphene sheet observed by transmission electron microscopy (TEM) (Inkson, 2016). Other defects such as pentagons, heptagons and their combinations, vacancies, adatoms, edge dislocations, grain boundaries, cracks, surface impurities, presence of functional groups on the flakes, among others, can also be found (Jiang *et al*., 2014).

In the production of graphene by mechanical or chemical exfoliation techniques, there is typically a variation in the thickness and diameter of the flake. This prevents the production of graphene with small areas and often results in folds at the edges (Johra; Lee; Jung, 2014). In these areas, there is a deviation in the coordination number of the crystal arrangement, resulting in excess energy and stress in the structure (MA *et al*., 2022a). In this type of preparation, environmental conditions may result in the presence of air-transported impurities. Meanwhile, the CVD method can generate many wrinkles, vacancies, and grain boundaries, which limit the electrical conductivity of graphene (Zhang; Xin; Ding, 2013a).

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1.5 ELECTRICAL PROPERTIES

High Electronic Mobility: Electrons in graphene move with exceptional mobility, 100 times greater than in silicon (Novoselov *et al*., 2004). This property makes it ideal for high-speed, low-power electronic devices (Geim; Novoselov, 2007).

Adjustable Semibandgap: Unlike other semiconductors, graphene has an adjustable semibandgap, which means its electrical conductivity can be modulated through chemical doping or an electric field (Ma *et al*., 2022b; (Han *et al*., 2017). This property makes it ideal for a wide range of electronic devices, such as transistors and diodes (Xu; Cao; Heath, 2009).

Optical Transparency: Graphene is a transparent material, transmitting up to 97% of visible light (Novoselov *et al*., 2004). This property makes it ideal for transparent touch screens and transparent electrodes in solar cells (liu 2020, han 2017).

1.6 CHEMICAL PROPERTIES

Chemically Stable: Graphene is chemically stable and corrosion-resistant, making it ideal for applications in harsh environments (Zhang *et al*., 2010), Biocompatible (Xu *et al*., 2009); Versatile Functionalization (Liu, 2019).

The exceptional properties of graphene make it a promising material for various innovative applications across different fields, such as electronics, nanotechnology, biomedicine, and energy. The combination of its unique mechanical, electrical, chemical, and optical properties open a range of possibilities for the development of new devices and materials with innovative and revolutionary features.

1.7 MAIN CHARACTERIZATIONS

Raman spectroscopy is a widely used technique for characterizing graphene and graphene oxide, identifying bond types, and determining crystal lattice disorder. The Raman spectra of carbonaceous materials show characteristic peaks between 1000 and 1800 cm^{-1}, dominated by three main bands: G, D, and D' bands, with visible and infrared excitation energy peaks (Camargos *et al*., 2017). As illustrated in Figure 4.

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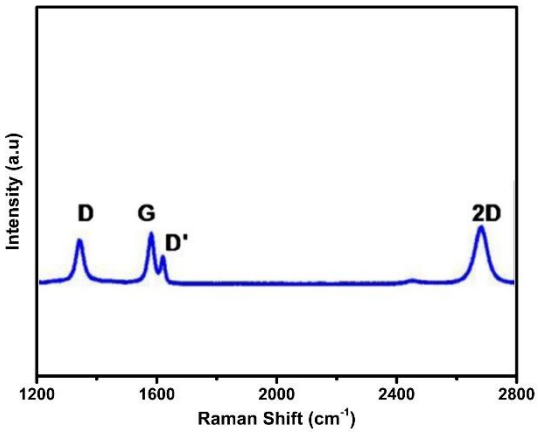
Figure 4

Raman spectra and typical graphene bands



Source: Zafar (2013).

The G band in Raman spectroscopy indicates the type of graphene, while the D band indicates disorder due to defects in the carbon ring structure. The D' band provides additional information about the material's structure and defects. Other peaks, such as the 2D band, reveal the number of graphene layers. Analyzing these bands provides detailed information about the structural and electronic properties of graphene. (Lobo *et al*., 2005).

With the power of Raman spectroscopy, scientists continue to uncover the secrets of graphene and its derivatives, paving the way for a future filled with technological innovations and transformative applications across various fields of knowledge (Nanda, *et al*., 2016).

1.8 ELECTRON MICROSCOPY

Electron Microscopy (EM), including Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), are widely used techniques for the characterization of various materials, particularly graphene (Bachmatiuk et al., 2015; Inkson *et al*., 2016).

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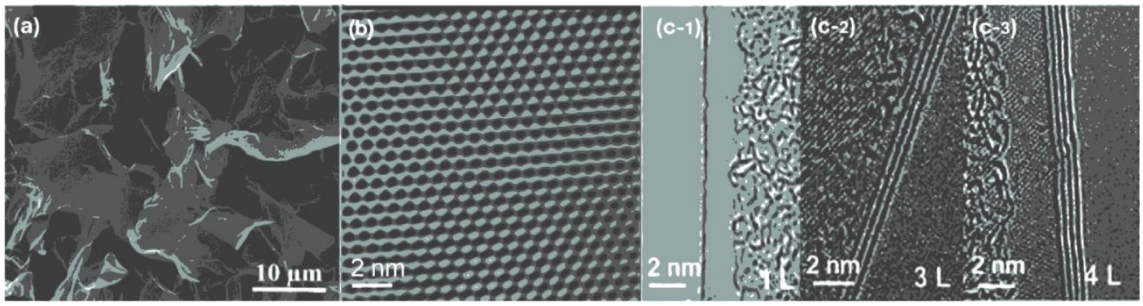
Figure 5

SEM image of the graphene sheet structure. (b) TEM image of the hexagonal structure of the graphene nanosheet. (c) HRTEM micrographs of the multilayered structure

(a) 

Source: Yasin (2018); Zafar (2013); Adetayo; Runsewe, *et al*. (2019).

SEM provides high-resolution images of the graphene surface, revealing details of the topography, roughness, and presence of defects such as folds, wrinkles, and holes (Figure 5 (a)). On the other hand, TEM enables a more detailed analysis of the internal structure and thickness of graphene sheets and their structures (Figure 5 (b and c)). This technique allows for the visualization of defects, folds, and multilayers in graphene sheets and their variations (Mbayachi, *et al*., 2021).

TEM is commonly employed in conjunction with SEM to obtain a comprehensive morphological and structural characterization of graphene-based materials. In summary, SEM and TEM are essential tools for the detailed characterization of the morphology, structure, and composition of graphene and its derivatives, providing crucial information for the development and application of these advanced materials (Shen; Oyadiji, 2020).

1.9 X-RAY DIFFRACTION (XRD)

X-ray diffraction is a non-destructive analytical technique used to characterize crystalline materials. It allows the determination of atomic and molecular structures, phase identification, and detection of defects in the crystal lattice. This versatile technique plays a fundamental role in various fields of knowledge, from materials science to chemistry, being used for the study of defects and imperfections, phase and compound identification (Silva, 2020).

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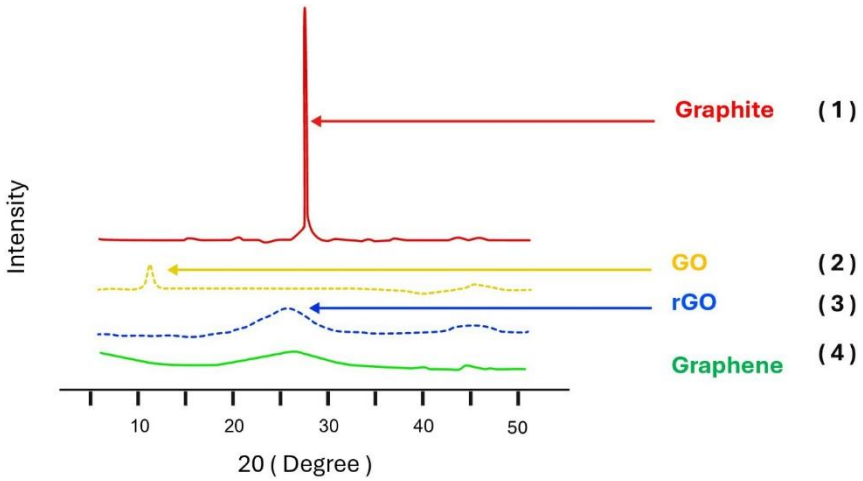
Figure 6

XRD spectra: (1) Graphite; (2) Graphene oxide (GO); (3) Reduced graphene oxide (rGO) and (4) Graphene



Source: Johra, Lee, Jung, (2014); Tiwari *et al*. (2020).

Pure graphene has a weak XRD signal, which makes it useful for studying the stacking order in multilayer graphene and graphene films. Figure 6 shows the XRD spectrum of graphite, GO, rGO and graphene. The diffractogram reveals a sharp diffraction peak at 26.6°, indicating a well-defined crystalline structure of graphite (Figure 6 (1)), GO shifts to 10° (Figure 6 (2)), the rGO is observed at the position of 24.8° (Figure 6 (3)) and graphene has a peak at 25.4° (Figure 6 (4)) with lower intensity (Yasin, 2018).

1.10 METHODS FOR OBTAINING GRAPHENE AND ITS INFLUENCE ON ELECTRICAL PROPERTIES

The production of graphene from graphite by chemical exfoliation or by oxidation-reduction is referred to by the methods of Brodie (Chernova *et al*., 2023), Staudenmaier (Sheshmani; Fashapoyeh, 2013), and Hummer (Hack *et al*., 2018). All three methods involve varying levels of graphite oxidation. Brodie and Staudenmaier used a combination of potassium chlorate ($KClO_3$) with nitric acid (HNO_3), while the Hummer method involves treating graphite with potassium permanganate ($KMnO_4$) and sulfuric acid (H_2SO_4).

In addition to the chemical exfoliation method for obtaining graphene, other methods are reported in the literature, such as chemical vapor deposition (CVD) and liquid phase exfoliation (LPE) (Liu *et al*., 2022). Compared to the other two methods (CVD and liquid exfoliation) for obtaining graphene, the Hummer method stands out for its relatively low

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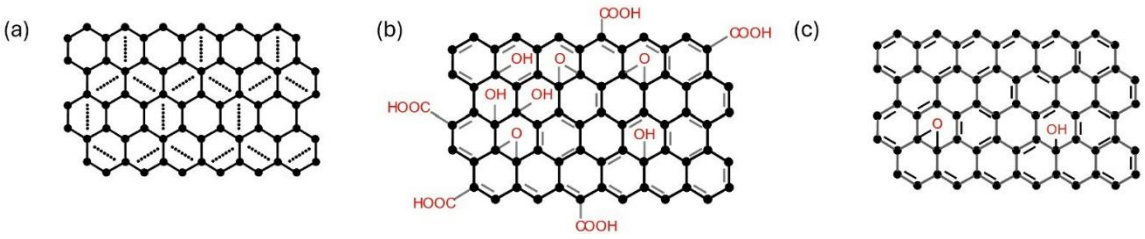
production cost, simple operation, speed, safety, lower pollutant generation, and high yield of around 92.2% graphite powder mass (Zhu et al., 2010; (Alshamkhani *et al*., 2021).

The reduction process of oxidation begins with the reaction of natural graphite with strong acid and powerful oxidizing agents while in ultrasonic dispersion. Subsequently, the oxygenated groups of graphene oxide are removed from the surface through the addition of a reducing agent, resulting in the production of reduced graphene (Kavyashree *et al*., 2020). Figure 7 shows the forms of graphene.

Figure 7

(a) Graphene, (b) Oxide graphene, (c) Reduced graphene



Source: Lalire; Longuet; Taguet, (2024).

The structure of monolayer graphene consists of a single carbon atom positioned on hexagonal vertices. Each atom forms covalent bonds with three other atoms, sharing four electrons in their orbits. These strong bonds provide structural stability, with the fourth electron occupying positions above or below the plane (Rezende, 2014).

In Figure 8 (a) Edges of graphene sheets show folds and wrinkled sheets. (b) Formation of a hole in a suspended graphene layer. (c) Graphene sheets displaying grain boundaries. (d) Nanobubbles are present in graphene sheets. (e) GO consists of a random distribution of oxidized areas with oxygen-containing functional groups combined with non-oxidized regions where most carbon atoms maintain sp^2 hybridization. (f) Stone-Wales defect (SW), formed by the rotation of a carbon-carbon bond by 90. (g) Single vacancy (SV) in the lattice refers to a single missing atom. (h) sp^3 defects produced by graphene chlorination. (i) Transition-metal (TM) atoms adsorbed on a perfect graphene sheet (adatoms).

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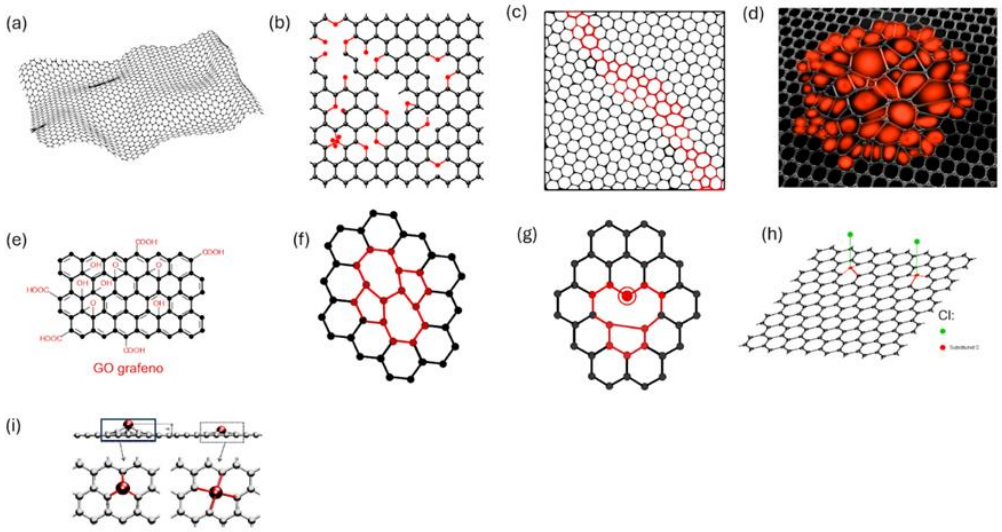
Figure 8

Defects in the graphene sheet structure



Source: Biró; Lambin (2013); Andrei; Li, Du (2013); Yang, *et al*. (2018); Bhatt; Kim; Kim (2022).

In the process of obtaining graphene through mechanical or chemical exfoliation, there is typically variation in thickness and flake diameter. This results in graphene with small areas and folds at the edges (Jiang *et al*., 2014). These areas exhibit a deviation in the coordination number of the crystal arrangement, leading to excess energy and structural stress (Qi; Cao; Park, 2013). In such preparations, environmental conditions can result in the presence of airborne impurities. On the other hand, the CVD method can generate wrinkles, vacancies, grain boundaries, which limit the electrical conductivity of graphene (Zhang; Xin; Ding, 2013).

1.11 INFLUENCE OF THE CHEMICAL EXFOLIATION METHOD ON GRAPHENE CONDUCTIVITY

Boychuk *et al*. (2019) studied the structure, morphology, and electrical conductivity of graphene oxide using Hummer GO(H) and Marcano-Tour GO(MT) methods. The electrical conductivity of GO(H) graphene was 0.02 S m^{-1} and 0.08 S m^{-1} at room temperature and 1000 Hz. The change in conductivity corresponds to charge hopping transfer mechanisms. The study by Clifford et al. (2024) used the liquid phase exfoliation (LPE) method to produce graphene. The product was then centrifuged at different speeds, with the lowest speed yielding smaller nanosheets (200 nm). The conductivity of the graphene was measured, with the lowest speed resulting in a maximum conductivity value of 2.8 x 10^4 S m^{-1}. The research highlights the potential of LPE in producing graphene.

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Xiong and colleagues' (2017) study on chemical exfoliation of graphene revealed that agitation during the process affects the efficiency of sulfuric acid intercalation between layers of graphite in the oxidation of potassium permanganate and the reducing agent graphene oxide. They produced graphene oxide dispersion using stirring at 100, 300 and 500 r min.$^{-1}$ and measured its electrical resistivity. The study found that the speed of 300 r min.$^{-1}$ showed better electrical conductivity (47.8 S m^{-1}).

Deemer *et al*. (2017) also studied the influence of functionalization and the diameter of the precursor graphite on the exfoliation and conductivity of the graphene obtained by the modified Hummer and Marcano-Tour methods. Both methods used ascorbic acid (L-AA) and aqueous ammonia for pH adjustment as reducing agents.

Table 1, the conductivity of GO by the modified Hummer and Marcano-Tour methods is shown, considering the diameter of the precursor graphite (diameters Ø <100 m and Ø >420 m). Using FTIR and TGA characterization, they observed that the precursors with larger diameters (Ø >420 m) exhibited greater oxidized regions of the flakes and less resistance between the sheets.

Table 1

Conductivity of GO obtained by modified Hummer and Marcano-Tour methods

Synthesis Method	recursor graphite diameter (Ø / µm)	Conductivity (S cm^{-1})
Modified Hummer	<1000	0,51
Modified Hummer	>420	52,6
Marcano-Tour	<100	0,53
Marcano-Tour	>420	16,7

Source: Deemer *et al*. (2017).

Ridzuan et al. (2021) produced graphene oxide using the modified Hummer method for sensor applications. They mixed graphene oxide with silver nanoparticles in a PMMA matrix, producing PMMA-GO and PMMA-Ag-GO nanocomposites. PMMA-Ag-GO nanocomposites showed higher electrical conductivity (3.71 x 10^{-10} S cm^{-1}).

1.12 INFLUENCE OF THERMAL REDUCTION ON THE CONDUCTIVITY OF GRAPHENE VIA CHEMICAL EXFOLIATION

The study by Acik and Chabal (2013) found that annealing heat treatment significantly reduced the oxygen content in graphene oxide (GO) structure. Yong-zhen *et al*. (2012) used

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the modified Hummer method to produce graphene oxide films with controllable size. They used vacuum annealing heat treatment, placing the GO film in a quartz tube under vacuum and maintaining a constant temperature for 1 hour. The heat treatments were carried out at temperatures ranging from 200 to 1100 °C, as indicated in Table 2.

Table 2

Effect of heat treatment on conductivity of GO film

Condition (No.)	Annealing temperature (°C)	Conductivity (S cm^{-1})
1	200	$1,94 \times 10^{-1}$
2	300	$2,00 \times 10^{0}$
3	400	$7,91 \times 10^{0}$
4	500	$6,58 \times 10^{0}$
5	600	$6,33 \times 10^{0}$
6	700	$9,98 \times 10^{0}$
7	800	$2,57 \times 10^{1}$
8	900	$2,78 \times 10^{1}$
9	1000	$1,43 \times 10^{2}$
10	1100	$5,36 \times 10^{2}$

Source: Yong-Zhen *et al*. (2012).

In Table 2, it is observed that conductivity increases as the temperature of the heat treatment increases. This behavior in conductivity was attributed to the removal of some oxygen-containing functional groups in the film, which led to the reduction of some sp^3 carbon atoms to sp^2 carbon atoms.

Other studies have utilized the reduction of GO by heat treatments and have examined its influence on conductivity, such as the work of (Vianelli *et al*., 2015) who produced OG by the modified Hummer method. They conducted high vacuum annealing heat treatments at various annealing temperatures for 1 hour. The conductivity values are shown in Table 3, in ascending order of temperature and conductivity, it is noted that with the increase in annealing, the conductivity of GO increased. With reduced GO, the sp^2 conjugated network is restored, but high temperatures can induce structural defects.

Table 3

Effect of Annealing Temperature on GO Conductivity

Condition (No.)	Annealing temperature (°C)	Conductivity (S cm^{-1})

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1	200	27.24
2	300	282.48
3	500	943.39
4	600	2,994.01
5	700	5,874.95
6	940	9,803.92

Source: Vianelli *et al*. (2015).

Maraschin *et al*. (2018) obtained graphene oxide from graphite powder using a modified Staudenmaier method. They used sulfuric acid, nitric acid, potassium chlorate, and hydrochloric acid to remove sulfate ions. The suspension was dried in a muffle furnace and heated to 1000 °C. The electrical conductivity of graphene oxide and reduced graphene oxide was measured, with higher conductivity for rGO due to the reduction process, and results of 60 S cm^{-1} were obtained. Table 4 presents a summary of the electrical conductivity values obtained by the chemical exfoliation method.

Table 4

Data from work on obtaining graphene by chemical exfoliation

Obtaining method	Conductivity (S m^{-1})	Author
Chemical exfoliation (Hummer)	2.0×10^{-2}	Boychuk *et al*. (2019)
Chemical exfoliation (Marcano-Tour)	8.0×10^{-2}	Boychuk *et al*. (2019)
Liquid phase exfoliation (LPE)	2.8×10^{4}	Clifford *et al*. (2024)
Chemical exfoliation (Hummer)	2.0×10^{-2}	Xiong; Huang; Wei, (2017)
Chemical exfoliation (Hummer)	1.5×10^{-3}	Zapata-hernandez *et al*. (2022)
Chemical exfoliation (modified Staudenmaier Method)	9.8×10^{3}	Ridzuan *et al*. (2021)
Obtaining method	Conductivity (S cm^{-1})	Author
Chemical exfoliation (Marcano-Tour)	1.6×10^{1}	Deemer *et al*. (2017)
Chemical exfoliation (Hummer)	5.2×10^{1}	Deemer *et al*. (2017)
Chemical exfoliation (modi- fied Stau- denmaier Method)	6.0×10^{1}	Maraschin *et al*. (2018)

Source: Author.

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1.13 INFLUENCE OF THE CHEMICAL VAPOR DEPOSITION (CVD) METHOD ON GRAPHENE CONDUCTIVITY

CVD is the most effective method for producing high-quality graphene films, but challenges remain in synthesis and transfer methods to maintain film quality.

Vlassiouk *et al*. (2011) studied graphene production using CVD, focusing on thermal and electrical properties and disorder. They found that low deposition temperature significantly affects disorder, despite its gradual increase, it exhibits high thermal conductivity (10^2-10^3 W K^{-1} m^{-1}) and low electrical resistivity (10^{-3} x 10^5).

Cao *et al*. (2019) found that incorporating graphene into metals such as Cu, Al and Ag found to have an electrical conductivity 3000 times higher than most pure metal conductors at room temperature. The graphene used as reinforcement had a conductivity of 117%, 58.1 x 10^6 S m^{-1} for the Gr/Cu composites with the thinnest Cu layers.

Park *et al*. (2016) presented a way to improve the electrical performance of graphene by controlling the density and height of wrinkles after transferring to SiO_2/Si substrates, varying the cooling rates during manufacturing. This route improved the electrical properties, such as higher electron/hole mobility, in addition to reducing the sheet resistance.

Table 5 shows some examples of the properties of CVD graphene. Graphene has many other remarkable properties that have not been listed here. The values of the properties of graphene can vary depending on the production conditions and the quality of the material. The values of the information mentioned above can be found in Table 5.

Table 5

Property data of graphene obtained by CVD

Obtaining method	Properties	Author
CVD	Conductivity = 10^{-1} - 10^{-3} S m^{-1} S m^{-1}	Ramiréz *et al*. (2023)
CVD	Electrical conductivity of xy = 58,1 × 10^6 S m^{-1}	Cao *et al*. (2019)
CVD	High thermal conductivity = 10^2-10^3 W K^{-1} m^{-1}; Low electrical resistivity = 10^3-3 x 10^5	Vlassiouk *et al*. (2011)
CVD	Electrical conductivity of monolayer graphene flakes = 1,46 ± 0,82 × 10^6 S m^{-1}; Electrical conductivity of rGO flakes = 2,3 ± 1,0 S m^{-1}	Lim *et al*. (2021)
CVD	Sheet resistance = 600 sq^{-1}; Transmittance (550 nm) = 96,5%; Carrier mobility = 5080.5 cm^2 V^{-1} s^{-1}	Zhang *et al*. (2012).

Source: Author.

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2 METHODOLOGY

We conducted a systematic review with an expanded scope (scoping) to map graphene synthesis routes and their effects on electrical properties, structured according to the PRISMA 2020/PRISMA-S guidelines; The search covered Web of Science, Scopus, IEEE Xplore, ScienceDirect, Wiley Online Library, SpringerLink, ACS Publications, RSC Publishing, PubMed, SciELO, Portal CAPES, and Google Scholar, with the last update on September 2, 2025, covering publications between 2004 and 2025 (analytical emphasis on 2022–2025). The strategies (adapted by database) combined controlled and free terms e.g., (graphene OR “graphene oxide” OR rGO OR “few-layer graphene”) AND (“chemical vapor deposition” OR CVD OR “liquid phase exfoliation” OR LPE OR “oxidation–reduction”) AND (“electrical conduct*” OR conductivity OR “sheet resistance” OR mobility OR resistivity) with filters for document type (original articles) and language (English/Portuguese/Spanish). References were exported (RIS/BibTeX), deduplicated in Zotero (DOI/title/author/year with fuzzy matching), and screened in Rayyan by two independent reviewers, with conflicts resolved by a third reviewer.

Eligibility criteria (PEOS): P graphene-based materials (mono/few-layer, GO, rGO, FLG); E synthesis method (CVD, LPE, oxidation-reduction and variants, process and transfer parameters); O electrical metrics (conductivity/resistivity, sheet resistance, mobility) and related structural markers (Raman, XRD, TEM/SEM); S original experimental studies; reviews, editorials, patents without experimental data, preprints when a published version already existed, and works without quantified electrical data were excluded. Extraction (by pairs, with cross-checking) followed a standardized form covering metadata, synthesis parameters, structural characterization, electrical measurement architecture, environmental conditions, sample size, and statistics; units were harmonized (SI) and test conditions preserved.

Methodological quality and risk of bias were assessed using a checklist adapted for experimental studies on materials (process details, traceability of inputs, calibration/instrumentation, T/UR control, repeatability, Raman/XRD/TEM consistency), classifying each item as low/some/high risk. The synthesis integrated a qualitative approach (by synthesis route and post-processing, relating ID/IG, I2D/IG, and microstructure to electrical results) and, when ≥3 studies were comparable, quantitative analysis with a random effects model (Hedges g SMD), heterogeneity (I^2, τ^2), sensitivity (leave-one-out) and

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publication bias (funnel plot and Egger's test, when n ≥ 10), as well as exploratory meta-regressions for sheet resistance and mobility with process predictors.

3 RESULTS AND DISCUSSION

Future Prospects:

a) New synthesis techniques: Vlassiouk *et al*. (2011), (Cao *et al*., 2019), and Alshamkhani *et al*. (2021) suggest the development of new graphene synthesis techniques, such as methods based on ionic liquids or plasma synthesis, which can overcome the limitations of current methods and enable large-scale production of high-quality material.

b) Improvement of transfer techniques: Park *et al*. (2016) propose the enhancement and development of more efficient transfer techniques, such as dry methods or polymer-based methods, which can minimize damage to the graphene structure and facilitate its integration onto various substrates.

c) Interface engineering: Vlassiouk *et al*. (2011) highlights that engineering the interfaces between graphene and other materials can significantly improve its properties and pave the way for new applications.

d) Advanced functionalization: Park *et al*. (2016) suggest the development of new functionalization strategies, such as click chemistry or in-situ polymerization, which can provide greater control over graphene's properties and adapt it to even more demanding applications.

e) Comprehensive safety evaluation: Cao *et al*. (2019) emphasize the importance of in-depth studies on the long-term safety and toxicity of graphene, which are essential to ensure its safe use in products and devices.

Regarding the methods of obtaining graphene, CVD is the most efficient method for producing high-quality graphene, but concerns about toxicity, stability, and environmental impact need to be addressed. Research is ongoing to optimize growth methods for large-scale applications in electronic devices, such as ultra-thin flexible screens, smartphones, biosensors, nanorobots, and light cables in aircraft and satellites. The industry's high demand for graphene in these applications makes it a promising area of study.

Despite challenges in achieving graphene's full potential, continuous research and development can unlock its transformative potential in various sectors, including electronics, medicine, and energy, paving the way for a sustainable, technological, and prosperous future.

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4 CONCLUSION

Graphene emerges as a revolutionary material, opening doors to a future filled with promising possibilities. Through a thorough analysis of the methods of obtaining it and their impacts on electrical conductivity, this work offers a comprehensive view of graphene's potential to transform various areas.

Chemical exfoliation, a traditional method, has advantages such as simplicity and low cost, but faces challenges in the homogeneity and control of the graphene structure. On the other hand, chemical vapor deposition (CVD) stands out to produce high-quality films but requires improvements in synthesis and transfer to preserve the material's integrity. The search for optimized methods and the exploration of innovative applications are crucial areas for the advancement of graphene. The incorporation of graphene into metals demonstrates the potential to significantly increase electrical conductivity, paving the way for a new era of energy efficiency. Precise control of graphene's structure allows the improvement of its electrical properties, paving the way for next-generation electronic devices.

However, there are still challenges to be overcome, such as the large-scale production of high-quality graphene and the economic viability of its application in various areas. Continuous research and development are essential to overcome these obstacles and unlock the full potential of graphene. The future of graphene is promising, with applications extending from electronics and photonics to medicine and energy. It is crucial to continue investing in research and innovations to explore the full potential of this revolutionary material and build a more sustainable and technological future.

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