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Biomass-Derived Graphene Oxide in Heterogeneous Catalysis: A Review of Synthesis, Functionalization, and Reaction Kinetics

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ABSTRACT

Graphene oxide (GO) has emerged as a versatile nanomaterial in heterogeneous catalysis due to its two-dimensional structure, high surface area, and tunable surface chemistry. This review critically addresses whether biomass-derived GO can replace conventional graphite-based GO without sacrificing catalytic performance. To answer this, recent advances are examined in three interrelated areas: the sustainable synthesis of GO from biomass-derived precursors, functionalization strategies used to tailor its surface properties, and kinetic studies of reactions using GO and functionalized GO (FGO). Biomass-based synthesis routes via hydrothermal treatment, pyrolysis, and modified Hummers methods offer an environmentally friendly alternative to conventional graphite processing. These methods produce GO with surface area and oxygen content comparable to graphite-derived GO, while reducing reliance on non-renewable resources and supporting waste recycling. Both covalent and non-covalent functionalization approaches are critically compared. Covalent methods enhance stability and active site density, whereas non-covalent methods better preserve GO's structure. Particular attention is given to kinetic studies, which provide insights into how surface chemistry and functional group distribution influence reaction rates. The review concludes that with optimized synthesis and functionalization, biomass-derived GO can achieve catalytic performance comparable to graphite-derived GO while offering a lower environmental footprint. Nevertheless, additional research into scalable production and mechanistic kinetics is still required.

Keywords: Graphene oxide; functionalization; reaction kinetics; biomass; heterogeneous catalysis

INTRODUCTION

Graphene oxide (GO) has attracted considerable attention in scientific research and industrial applications due to its unique properties and potential for diverse uses. As a monolayer material derived from graphite, GO possesses remarkable structural characteristics, including high surface area, mechanical strength, and excellent thermal and electrical conductivity, making it a valuable candidate for various applications like sensors, energy storage, biomedical devices, and catalysis (Fan et al. 2015; Jiříčková et al. 2022). The oxygen-containing functional groups in GO, such as hydroxyl, carboxyl, and epoxy groups, enable easy functionalization, which enhances its versatility in different chemical reactions (Singh et al. 2016; Albero et al. 2019). The unique structure of GO consists of a single-atom-thick sheet of sp^2-hybridized carbon atoms decorated with these oxygen functionalities, which not only make GO hydrophilic and dispersible in water but also provide reactive sites for further chemical modifications. The presence of these groups significantly alters the electronic structure of the carbon lattice, creating a material that is electrically insulating yet chemically versatile. This adaptability highlights the importance of GO synthesis techniques and the subsequent customization of its properties for specific applications.

However, a critical question remains: can biomass-derived GO replace conventional graphite-based GO in heterogeneous catalysis without sacrificing performance? This review answers that question by systematically comparing synthesis routes, functionalization strategies, and kinetic outcomes.

The utilization of biomass as a precursor for GO has emerged as a promising approach. Composed of organic materials derived from plants, agricultural residues, or even industrial waste, biomass offers an eco-friendly and sustainable carbon source for producing graphene-like materials (Bahuguna et al. 2019; Sultana et al. 2025). The conversion of biomass to GO not only reduces environmental concerns associated with traditional graphite processing but also contributes to the effective management of waste materials (Xia et al. 2018). Additionally, employing a biomass-centered approach aligns with sustainable development goals (SDGs) by transforming waste materials into high-value products, thus fostering a circular economy in chemical production (Lou et al. 2012; Mohamed et al. 2023). The global push toward sustainability has intensified research into alternative carbon sources for advanced materials. Biomass, being renewable and widely available, presents an attractive option for large-scale GO production. Various types of biomass, including agricultural residues (sugarcane bagasse, rice husks, corn stover), forestry waste (wood chips, sawdust), and even municipal organic waste, have been investigated as potential precursors. The choice of biomass source significantly influences the properties of the resulting GO, including its surface area, oxygen content, and defect density.

Various methodologies have been employed to synthesize GO from biomass, including hydrothermal treatment, chemical oxidation, and pyrolysis (Bahuguna et al. 2019; Sultana et al. 2025). These processes take advantage of the naturally high carbon content in biomass, which can be converted into an oxygen-rich carbon framework through suitable treatment, thereby yielding GO with desirable properties for catalytic applications. Each synthesis method offers distinct advantages and limitations, which are critically examined in the following sections.

Functionalization of GO is critical to enhancing its catalytic performance and extending its applications as an acidic catalyst in heterogeneous reactions. Acidic catalysts play an essential role in driving important chemical reactions, such as esterification, dehydration, and hydrolysis, which are vital processes in industrial chemistry and green synthesis technologies (Garg et al. 2014; Movlaee et al. 2017). Various strategies have been attempted to enhance the acidic properties of GO through functionalization, including sulfonation, metal ion complexation, and the introduction of acidic groups (Gil-Gavilán et al. 2024; Kuanyshbekov et al. 2024). These modifications improve catalytic activity, stability and reusability, making them suitable for use in continuous and large-scale processes (Gil-Gavilán et al. 2024).

Functionalized GO (FGO) offers distinct advantages in heterogeneous catalysis. For example, sulfonic acid groups introduced onto the GO surface enhance its catalytic activity in converting biomass-derived carbohydrates to value-added chemicals (Gil-Gavilán et al. 2024). The unique surface characteristics of FGO facilitate reaction mechanisms through increased accessibility of active sites, better substrate binding, and enhanced reaction kinetics (Garg et al. 2014). The two-dimensional nature of GO provides a large accessible surface area, allowing reactant molecules to interact efficiently with catalytic sites.

The utilization of GO and FGO in catalytic processes has become one of the most explored topics due to their influence on the kinetics of catalytic reactions. Understanding reaction rates and mechanisms is essential for optimizing catalysis. For instance, GO has been extensively studied as a support material for catalytically active metals such as platinum or palladium to improve reaction rates in hydrogenation and oxidation reactions (Nadaraia et al. 2021). Its effectiveness as a catalyst or support depends on optimizing surface interactions. Moreover, functional groups on GO provide active sites that can alter the reaction pathways and optimize the energy associated with the reactions, thus significantly affecting the kinetics (Utkan et al. 2023).

This review examines recent progress in three interrelated areas: the synthesis of GO from biomass-derived precursors, functionalization strategies to modify surface properties, and kinetic studies of reactions catalyzed by GO and FGO. The following sections detail current GO synthesis technologies, surface modification approaches, and representative kinetic studies and applications involving GO and FGO.

SYNTHESIS OF BIOMASS-DERIVED GRAPHENE OXIDE

CONVENTIONAL VS. BIOMASS-BASED SYNTHESIS

Traditional methodologies for synthesizing GO predominantly revolve around chemical oxidation techniques, such as the Hummers method and its modifications. These methods typically utilize graphite as the precursor, oxidizing it with strong oxidizing agents like potassium permanganate ($KMnO_4$) and sulfuric acid (H_2SO_4) (Kotchey et al. 2011; Wang et al. 2011). The conventional Hummers method, developed in 1958, involves the oxidation of graphite in a mixture of concentrated H_2SO_4, sodium nitrate ($NaNO_3$), and $KMnO_4$. Subsequent modifications, such as the modified Hummers method, eliminate the use of $NaNO_3$ and employ a larger quantity of $KMnO_4$, resulting in a higher degree of oxidation and reduced toxic gas emissions.

However, the utilization of biomass as a carbon source offers a more sustainable paradigm, converting lignocellulosic materials or organic waste directly into GO. The resulting material's quality and yield depend heavily on the biomass source, pre-treatment conditions, and oxidation extent (Peng et al. 2019; Verástegui-Domínguez et al. 2022).

COMPARISON OF SYNTHESIS METHODS

Generally, there are four main routes exist for synthesizing GO from biomass: hydrothermal treatment, pyrolysis followed by oxidation, modified Hummers method, and green approaches. Table 1 summarizes their key features, advantages, and limitations. The hydrothermal process typically operates under high-temperature and high-pressure water conditions, where water acts both as a solvent and a reactant to promote the hydrolysis of biomass components such as cellulose, hemicellulose, and lignin (Mohapatra et al. 2024). The resulting carbon-rich intermediates then undergo oxidation, usually with strong acids or oxidizing agents, to introduce oxygen functional groups and exfoliate the carbon structure into graphene oxide sheets. For example, biomass such as bamboo or coconut husk can be treated under hydrothermal conditions to produce a colloidal suspension that, after chemical oxidation, yields GO with abundant oxygen functional groups (Lee et al. 2023). A key strength of this method is its ability to work with wet biomass without prior drying, and it is milder and more energy saving than pyrolysis. However, the yield is typically low, and the process requires a longer post-treatment oxidation step. A significant drawback is that the hydrothermal step alone does not produce fully oxidized GO. Subsequent chemical oxidation is mandatory, which reintroduces chemical waste. Compared to other methods, hydrothermal offers good energy efficiency but poor yield (Bahuguna et al. 2019; Sultana et al. 2025).

TABLE 1. Summary of biomass-derived GO synthesis methods

Synthesis Method	Key Feature	Advantage	Limitation
Modified Hummers	High-quality GO with large surface area	Highest yield; well-understood	Hazardous acids; acidic wastewater
Hydrothermal + oxidation	Wet biomass with high moisture content	No drying needed; energy savings	Low yield; requires post-oxidation
Pyrolysis + oxidation	Scalable production from biomass	Kilogram-scale; high carbon precursor	Energy-intensive
Green/enzymatic	Environmental friendly and sustainable approach	No hazardous reagents; waste recycling	Lab scale only; high cost

The pyrolysis process involves the thermal decomposition of biomass in the absence of oxygen, producing three main products: biochar (solid), bio-oil (liquid), and syngas (gas). The composition of biochar depends on the biomass source and pyrolysis conditions. The biochar derived from pyrolysis possesses a partially graphitic structure with some oxygen functional groups, which can be further oxidized to increase the oxygen content and exfoliate the material into GO (Onen et al. 2023). Agricultural waste fibers like sugarcane bagasse or rice husk can be treated with strong acids to yield GO (Liou et al. 2023; Said et al. 2023). This method produces a high-carbon precursor (biochar) and is scalable to kilogram levels, while generating less chemical waste. However, it is energy-intensive, where the high-temperature step may offset the renewable benefit of biomass. Among all methods, pyrolysis offers the best scalability but carries the highest energy footprint.

Modified Hummers method applies the classical graphite oxidation protocol to biomass-derived carbon materials. The process involves three steps: (1) *Preparation of precursor* where biomass is subjected to pre-treatment, often involving drying and grinding, to produce fine particles that facilitate reactivity during oxidation (Uçar et al. 2019), (2) *Oxidative treatment* where the pre-carbonized biomass are combined in sulfuric acid, followed by the slow addition of $KMnO_4$ to form GO by disrupting the structural integrity of the carbonaceous material and introducing oxygen functionalities through oxidative action (Hossain & Kosei, 2024; Dziejarski et al. 2025), and (3) *Post-oxidation processing* where the GO suspension is then further treated by diluting it with water and hydrogen peroxide (H_2O_2) to terminate the oxidation reaction and facilitate the exfoliation to GO (Eskitoros-Togay et al. 2023; Nandakumar et al. 2024). This method achieves the highest yield among biomass routes and benefits from well-understood chemistry, producing GO with large surface area (Said et al. 2023; Hossain & Kosei, 2024). However, the use of concentrated acids generates acidic wastewater that requires extensive washing, thereby partially offsetting sustainability gains (Nandakumar et al. 2024; Dziejarski et al. 2025). Hence, for applications

requiring high-quality GO with large surface area, modified Hummers method is a good choice despite its chemical waste; but for applications that prioritize sustainability, other methods may be preferable.

With increasing environmental concerns, research efforts are also focusing on more sustainable and green approaches to synthesize GO from biomass. Methods such as enzymatic oxidation employs specific enzymes to catalyze the oxidation of biomass-derived carbon materials. These enzymes operate under mild conditions and are highly selective, offering the potential for controlled and environmentally benign GO synthesis. Additionally, with the use of biowaste precursors like spent coffee grounds and fruit peels (Liou et al. 2023; Said et al. 2023), these methods avoid hazardous reagents and support waste recycling, aligning well with circular economy principles (Onen et al. 2023; Castillo et al. 2024). However, the high cost of enzymes, their low yield and limited stability, and the difficulty of recovering and reusing the enzyme remain significant challenges. Although enzymatic oxidation is not yet industrially viable, it represents an important direction for future research, particularly if enzyme recycling and immobilization techniques can successfully reduce costs.

CHARACTERIZATION OF BIOMASS-DERIVED GRAPHENE OXIDE

The quality and properties of biomass-derived GO can be assessed using a combination of characterization techniques. Advanced analyses such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) can be employed to examine the structural integrity and confirm the successful oxidation and formation of GO from biomass (Adel et al. 2021). XRD analysis is particularly useful for confirming the oxidation of biomass-derived carbon materials (Peng et al. 2019). The characteristic (002) diffraction peak of graphite, typically observed at around 26.5°, shifts to lower angles (typically 10–12°) upon oxidation, indicating an increase in interlayer spacing due to the introduction of oxygen functional groups (Park et al. 2008; Verástegui-Domínguez et al. 2022).

FTIR spectroscopy provides information about the functional groups present on the GO surface (Si & Samulski, 2008; Adel et al. 2021). Typical absorption bands include a broad O–H stretching vibration at around 3400 cm^{-1}, a C=O stretching vibration at around 1720 cm^{-1}, and C–O stretching vibrations at around 1220 and 1050 cm^{-1} (Liou et al. 2023; Said et al. 2023). SEM imaging reveals the morphology of the synthesized GO, typically showing wrinkled, flake-like structures with lateral dimensions ranging from hundreds of nanometers to several micrometers (Adel et al. 2021; Mohapatra et al. 2024).

Raman spectroscopy is employed to assess the degree of disorder and defect density in the carbon lattice, typically through the intensity ratio of the D and G bands (I_D/I_G). Higher I_D/I_G ratios indicate greater defect densities, which can be either beneficial or detrimental depending on the intended application (Kim et al. 2020). Thermogravimetric analysis (TGA) is used to evaluate the thermal stability of GO and the composition of functional groups. The weight losses provide information about the degree of oxidation and the types of functional groups present (Li et al. 2021).

APPLICATIONS OF BIOMASS-DERIVED GRAPHENE OXIDE

Once synthesized, biomass-derived GO exhibits exceptional potential in heterogeneous catalysis. The large surface area of GO facilitates high loading capacity of active materials, resulting in improved catalytic performance (Fan et al. 2015). The increased surface area enables more substrate molecules to interact with the active catalytic sites, leading to enhanced reaction rates. Moreover, the presence of functional groups such as hydroxyl, carboxyl, and epoxy groups on the surface of GO significantly enhances its chemical reactivity, serving as anchoring sites for metal nanoparticles or organic molecules to tailor catalytic properties (Morales-Narváez & Merkoçi, 2012). In addition, GO-supported catalysts also show excellent stability under harsh reaction conditions, making them suitable for industrial applications to undergo multiple reaction cycles without significant loss of activity (Song et al. 2015). The ability to easily separate, recover, and reuse GO-based catalysts further demonstrates their practicality and cost-effectiveness (Mayakrishnan et al. 2020).

In oxidation reactions, GO acts as a catalyst for converting alcohols to carbonyl compounds using hydrogen peroxide or other oxidants (Alka et al. 2025). The presence of acidic functional groups on GO facilitates the activation of oxidants and the stabilization of reaction intermediates, leading to efficient and selective oxidation processes. In reduction reactions, palladium supported on GO selectively reduces nitroarenes to amines under mild conditions (Ren et al. 2014). The strong interaction between palladium nanoparticles and the GO support prevents aggregation and provides stable catalytic activity over multiple cycles.

Beyond these classic reactions, GO-based catalysts are employed in advanced oxidation processes for wastewater treatment, effectively degrading dyes, pharmaceuticals, and pesticides (Gupta et al. 2016; Kumar et al. 2023). They also play a role in CO_2 conversion,

turning the greenhouse gas into valuable fuels such as methanol or syngas via reduction or dry reforming (Alamgholiloo et al. 2020; Bhattacharya et al. 2020). The high surface area and functionalization potential of GO provide suitable environments for anchoring active metal nanoparticles and promoting the adsorption and activation of CO_2 molecules. Moreover, GO's high adsorption capacity enables composite catalysts that remove heavy metals from aqueous solutions, facilitating degradation of heavy metals and organic pollutants simultaneously (Mayakrishnan et al. 2020; Amiri-Zirtol et al. 2023).

While the synthesis of GO from biomass offers a promising route toward more sustainable materials, several challenges remain. It is crucial to optimize the synthesis processes to ensure consistent quality and yield across different biomass sources, which can vary significantly in composition. There is also a need for extensive research into scale-up methodologies that enable the transition from laboratory-scale synthesis to industrial applications (Li et al. 2021; Neena, 2024). A key unanswered question is whether the performance differences among synthesis methods justify their trade-offs, e.g., does the higher yield and surface area of modified Hummers outweigh its environmental footprint compared to pyrolysis? Future research should address this through systematic comparative studies using identical catalytic tests across materials from different synthesis routes.

FUNCTIONALIZATION OF GRAPHENE OXIDE

OVERVIEW AND IMPORTANCE

The intrinsic properties of GO can be enhanced through functionalization to promote its activity, stability, and compatibility with other materials (Si & Samulski, 2008; Li et al. 2015). These modifications typically introduce specific functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and amino ($-NH_2$) groups, which can alter GO's interactions with other molecules and improve its performance for targeted applications (Yu et al. 2020; Nizami et al. 2022). Using covalent or non-covalent methods, functionalization enables the tailoring of GO's chemical, physical, and mechanical properties, broadening its use across catalysis, electronics, environmental remediation, and biomedicine.

The choice between covalent and non-covalent functionalization depends on the intended application and the desired properties of the final material. Covalent functionalization offers stronger and more permanent modifications, making it suitable for applications requiring long-term stability and resistance to leaching. Non-covalent functionalization offers the advantage of preserving the intrinsic properties of GO, such as its electrical conductivity and mechanical strength, making it suitable for applications where these properties are critical.

COVALENT FUNCTIONALIZATION METHODS

Covalent functionalization involves the formation of strong chemical bonds between the functional groups and the GO structure, often producing substantial property changes. Common covalent functionalization methods include esterification with carboxylic acids and amidation with amines, which increase the surface reactivity of GO and enhance its compatibility with polymers for composite materials (Park et al. 2008; Yu et al. 2020). For instance, amino-functionalized GO shows improved adsorption capacities and increased electrical conductivity (Li et al. 2015; Ahmad & Kumar, 2024). However, a notable drawback is that the amine groups can become protonated under low pH conditions, which reduces catalytic activity (Krasteva et al. 2019).

Click chemistry is a highly efficient way to functionalize GO, allowing for the selective addition of functional groups via simple and highly reliable reactions, such as azide-alkyne cycloaddition. The reaction proceeds under mild conditions with high efficiency and selectivity, allowing for the attachment of a wide range of functional groups without affecting the integrity of the GO structure. This approach has been used to introduce various biomolecules onto the GO surface, enhancing its applicability in biomedical fields like drug delivery and imaging (Compton & Nguyen, 2010; Ahmad & Kumar, 2024).

Reduction is another functionalization pathway. GO can be reduced chemically, thermally, or electrochemically to yield reduced graphene oxide (rGO), with new functional groups introduced simultaneously during the process (Yu et al. 2020). The reduction process removes oxygen functional groups from GO, restoring some of the electrical conductivity and structural integrity of pristine graphene. The degree of reduction can be controlled by the choice of reducing agent and reaction conditions, allowing for tuning of the resulting rGO properties. For example, using hydrazine as a reducing agent, it can yield functionalized rGO with varied electronic properties suitable for different applications, including energy storage devices (Ahmad & Kumar, 2024).

Functionalization via introduction of acidic functional groups onto GO can transform it into an effective acid catalyst. Sulfonation, sulfonic acid derivatization, and metal ions complexation have been explored to enhance its catalytic efficacy in reactions such as esterification, dehydration, and hydrolysis (Golestanzadeh & Naeimi,

2019; Habibzadeh et al. 2019). Sulfonation introduces sulfonic acid groups (-SO_3H) onto GO via reaction with concentrated H_2SO_4 to increase its acidity. The enhanced acidity of sulfonated GO provides high catalytic activity for acid-catalyzed reactions, while its solid nature allows for easy separation and recyclability. For instance, Gil-Gavilán et al. (2024) reported an increase of glycerol acetalization conversion using sulfonated GO. The presence of Brønsted acid sites is vital for the catalytic reactions as they enhance proton transfer (Poulose et al. 2025). Although sulfonation significantly increases acidity, a key concern is that the sulfonic groups may hydrolyze under hydrothermal conditions. Hence, multi-cycle stability test is required to validate its applicability.

Carboxylation and amination are also important covalent functionalization strategies. Carboxylation increases the density of carboxyl groups on GO, enhancing its ability to chelate metal ions and its dispersibility in aqueous media (Yu et al. 2020). Amination introduces amino groups, which can form amide bonds with other molecules and act as basic sites for catalytic reactions (Yu et al. 2020; Nizami et al. 2022). The combination of different functional groups through sequential or simultaneous functionalization can create multifunctional GO materials with tailored properties for specific applications.

NON-COVALENT FUNCTIONALIZATION METHODS

Non-covalent functionalization involves interactions such as physical adsorption, π-π stacking, or hydrogen bonding between GO and functional materials without forming permanent chemical bonds. The oxygen functional groups on GO provide negatively charged sites that can interact with positively charged molecules and ions. Hydrogen bonding between the hydroxyl and carboxyl groups on GO and the functional groups of other molecules can provide additional stability for the functionalized material. For example, coating GO with polymers such as chitosan, gelatin, or polyvinyl alcohol enhances its mechanical or barrier properties for environmental remediation or sensing applications (Urbas et al. 2014; Mohammadrezaei et al. 2018; Manousi et al. 2020). This approach preserves GO's conjugated structure and electrical properties. However, the weaker attachment inherent to non-covalent methods can lead to metal leaching, causing losses in catalytic efficiency after several cycles.

Biomolecular functionalization method is also commonly used to modify GO with biomolecules such as proteins, nucleotides, or antibodies. This allows for the tailoring of GO, such as enhancing its biocompatibility for biomedical uses in drug delivery systems and biosensing applications (Ahmad & Kumar, 2024; Zahakifar & Khanramaki, 2024). These biomolecules can be immobilized through van der Waals forces, electrostatic attractions, or hydrogen bonds, preserving the integrity and structure of the biomolecules.

Another approach involves immobilizing metal ions onto the GO surface, where metal-supported GO acts as a bifunctional catalyst. This methodology integrates the acidic properties from GO with the redox capabilities provided by metal like Pd, Ni, or Co, thereby expanding catalytic versatility and significantly improving reaction rates for various biomass transformation processes (Pothu et al. 2022; Li et al. 2024). The immobilization of metal ions typically involves the coordination of metal ions to the oxygen functional groups on GO, providing a stable anchoring site that prevents metal aggregation.

Despite significant advantages of FGO, functionalization may lead to a partial loss of GO's exceptional properties due to chemical alterations. Therefore, understanding the balance between functionalization and property retention is critical (Urbas et al. 2014; Yu et al. 2020; Salehi & Ahmadi, 2022). Moreover, the materials and processes used must also align with sustainability goals to minimize environmental impact. The development of green functionalization methods using environmentally benign reagents and solvents is an important area of research. The use of water as a solvent, biodegradable polymers for coating, and renewable chemicals for functionalization can significantly reduce the environmental impact of FGO production (Lee et al. 2009; Krasteva et al. 2019; Ahmad & Kumar, 2024). The design of functionalization strategies that minimize the use of hazardous reagents and the generation of waste is essential for the sustainable development of FGO materials. Additionally, future directions in the functionalization of GO should also explore new methods that enhance its catalytic efficiency and selectivity to expand the applicability of FGO in heterogeneous catalysis.

KINETICS OF GO- AND FGO-CATALYZED REACTIONS

FUNDAMENTAL KINETIC CONCEPTS

The kinetic study aims to elucidate the rates of chemical reactions and the factors that influence them. The relationship between reactants and products over time is fundamental to understanding chemical processes (Faria et al. 2012). The reaction rate is typically expressed as a rate law; for a simple first-order reaction, the rate of

reaction (-*r*) is proportional to the concentration of a single reactant A (C_A):

Rate of first-order reaction, $-r = kC_A$

The Arrhenius equation relates the rate constant (k) to the activation energy (E_a) for a reaction. It provides insights into how temperature influences reaction kinetics:

$k = A*\exp(-E_a/RT)$

where A is the frequency factor, R is the universal gas constant, and T is the absolute temperature.

In the context of GO and its derivatives, the high surface area and chemical reactivity of these materials significantly influence reaction kinetics. The diverse functionalization patterns of GO provide multiple active sites for reactions, leading to altered kinetic profiles compared to traditional catalytic systems (Boopathi et al. 2014; Duan et al. 2015). GO is composed of a single graphene layer functionalized with oxygen-containing groups, such as hydroxyl (-OH), carbonyl (-C=O), and carboxyl (-COOH). These functionalities are crucial in determining the electronic properties of the material and thus its reactivity (Abouimrane et al. 2010). Furthermore, the degree of oxidation and the specific nature of these functional groups can significantly impact the kinetics of GO-catalyzed reactions. The surface area of GO provides a large number of active sites for catalytic reactions, resulting in high catalytic activity. The oxygen functional groups on GO can act as both acidic and basic sites, providing versatility for catalyzing different types of reactions. The interactions between reactants and GO surface are influenced by various factors, including the nature of the functional groups, the degree of oxidation, and the reaction conditions (Boopathi et al. 2014; Duan et al. 2015).

KINETIC MODELS AND APPLICATIONS

To understand the kinetics of chemical reactions involving GO and FGO, sophisticated kinetic models can be applied. Many adsorption phenomena involving GO can be described using pseudo-first order and pseudo-second-order kinetics. The pseudo-first-order model assumes physical adsorption or weak interaction, while the pseudo-second-order model assumes that chemisorption is the rate-controlling step, which is particularly useful when bonding occurs between the adsorbate and adsorbent, such as with heavy metals and organic dyes (Pourbeyram, 2016). The applicability of both models aids in predicting how different operational variables affect overall reaction rates. For instance, a study by Wang & Yao (2020) on the adsorption of pollutants from water using GO reported a successful fit to the pseudo-second-order model, indicating that the adsorption pathway is governed by the availability of active sites on the GO surface.

Another critical aspect of kinetics concerns adsorption isotherms, which describe how molecules interact with a solid surface to form a film. Langmuir and Freundlich isotherms are widely utilized to model the binding of reactants to GO surfaces. The Langmuir model assumes monolayer adsorption onto a surface with a finite number of identical sites, while the Freundlich model accommodates heterogeneous surfaces with distributed site energies. For GO with mixed oxygen functionalities, the Freundlich model often provides a better description (Meng et al. 2012; Kim et al. 2020). Understanding these isotherms helps estimate maximum adsorption capacities and kinetic parameters for various metal ions and organic contaminants (Zhang et al. 2019; Kim et al. 2020).

Hydrogenation is a fundamental reaction employed in various fields including organic synthesis and petrochemical processes. The mechanism of hydrogenation on GO involves the adsorption of hydrogen molecules on the GO surface, followed by dissociation and transfer to the substrate. The presence of metal nanoparticles on GO significantly enhances the hydrogenation rate by providing active sites for hydrogen dissociation. Chua and Pumera (2014) explored the reduction of GO and its implications on hydrogenation kinetics, reporting that the catalytic behavior significantly changed as the degree of reduction varied. The reaction kinetics followed pseudo-first-order models, indicating the dependence of hydrogenation rates on reactant concentrations and active site availability. Another study by Dhopte et al. (2017) examined the relationship between the oxidation state of GO and its suitability as a catalyst for the hydrogenation. Their findings indicated that a higher degree of reduction correlates with increased catalytic activity, attributed to enhanced electron availability and subsequent stabilization of reaction intermediates.

Oxidation reactions facilitated by GO have been widely investigated due to the oxygen functional groups on its surface. The degree of oxidation of GO influences its catalytic activity in oxidation reactions, with reduced GO often showing higher activity than fully oxidized GO. The presence of residual oxygen functional groups in reduced GO can act as active sites for oxidation reactions. Fu et al. (2014) described the impact of sulfide ions on the reduction of GO and its oxidation kinetics. Their study indicated that the presence of sulfides accelerated the desorption of oxygen functionalities from GO, ultimately

altering its reactivity profile. Kinetic analyses showed enhancements in the oxidation process of phenolic compounds when using reduced GO compared to fully oxidized GO. Meanwhile, Zahakifar and Khanramaki (2024) studied the effectiveness of FGO in the oxidation of heavy metals from aqueous solutions, indicating that FGO outperformed unmodified GO due to its enhanced surface area and functional group activity. The pseudo-second-order kinetic model effectively described the adsorption process, demonstrating the interdependence of reaction rate constants and the initial concentration of metal ions.

Coupling reactions such as the Suzuki-Miyaura and Buchwald-Hartwig transformations rely heavily on the effectiveness of catalysts. The performance of GO-supported catalysts in coupling reactions depends on the distribution and size of metal nanoparticles, the nature of the support, and the functionalization of the GO surface. Sarvestani and Azadi (2017) examined Pd-decorated GO at varying levels of functionalization and reported significant enhancements in reaction rates and yields for the Buchwald-Hartwig amination of aryl halides. The reaction followed first-order kinetics with respect to the substrate concentration.

Environmental remediation applications have also been extensively studied due to GO's strong adsorption capability in removing various pollutants from aqueous solutions. Both GO and FGO are widely used as adsorbents for capturing heavy metals and organic pollutants, contributing significantly to environmental remediation efforts. The adsorption of heavy metals on GO typically involves electrostatic interactions, complexation with oxygen functional groups, and ion exchange (Pourbeyram, 2016; Manousi et al. 2020). The adsorption capacity and kinetics depend on factors such as pH, temperature, initial concentration, and the presence of competing ions. Functionalization with amino, carboxyl, or other groups can enhance the adsorption capacity and selectivity for specific metals (Wang & Yao, 2020; Zahakifar & Khanramaki, 2024). Onen et al. (2023) studied the kinetics of boron adsorption on GO, showing that adsorption occurs rapidly at the initial stage but gradually slows as available surface sites become saturated, in which consistent with a pseudo-second-order kinetic model.

Kinetic studies are also important to evaluate the efficiency and performance of energy-related systems utilizing GO and its derivatives. In supercapacitor applications, the electrochemical performance of GO-based electrodes depends on the specific surface area, electrical conductivity, and porosity of the material (Li et al. 2015). Reduced GO exhibits higher specific capacitance and rate capability compared to GO due to its enhanced electrical conductivity (Kuila et al. 2013). Functionalization with metal oxides, conducting polymers, or other materials can further improve the electrochemical performance (Ahmad & Kumar, 2024). A study by Kuila et al. (2013) reported the improvements in the physiochemical properties of reduced GO compared to pristine GO, making it effective as a supercapacitor electrode materials. Kinetic analyses in this study show that reduced GO demonstrates faster charge-discharge rates, attributed to reduced resistance and greater accessibility of electroactive sites on the electrode surface. Another research conducted by Wang et al. (2014) indicated that the adsorption kinetics of polycyclic aromatic hydrocarbons onto GO align with a pseudo-second-order model, suggesting chemisorption as a significant mechanism controlling the rate of adsorption in energy applications. These findings allow efficient prediction of how quickly materials can capture energy-related contaminants or ions.

CONCLUSION

GO has emerged as a highly adaptable material in heterogeneous catalysis, functioning both as an active catalyst and as a support across a broad range of reactions. This attractiveness is driven by the combination of high surface area, adjustable surface chemistry, and ease of functionalization. These features link fundamental materials science to practical catalytic applications where efficiency and sustainability are increasingly important.

Surface functionalization plays a central role in improving the catalytic behavior of GO. Through covalent modifications, such as the introduction of amine, carboxyl, or sulfonic acid groups, the surface reactivity of GO can be enhanced, improving interactions with reactants and active sites. These changes often lead to faster reaction rates and better selectivity in oxidation, reduction, and acid-catalyzed reactions. In contrast, non-covalent approaches tend to preserve the graphene structure while enabling the attachment of metals, polymers, or biomolecules. This ability to tune surface activity without compromising structural stability has made FGO valuable across applications ranging from organic synthesis to environmental remediation.

GO accelerates reaction rates through its large surface area and its capacity to stabilize transition states via tailored surface modification. These features effectively reduce the activation energy of many chemical reactions, leading to notable improvements in reaction efficiency. Moreover, functionalization allows the properties of GO to be tuned for specific chemical pathways, enhancing its selectivity and performance. Kinetic studies on both GO and FGO further confirm their enhanced reactivity, supporting their use in various applications.

Returning to the central question of this review: can biomass-derived GO replace conventional graphite-based GO without sacrificing performance? The answer is conditionally affirmative. With optimized functionalization and consistent synthesis, biomass-derived GO can achieve catalytic performance comparable to or better than graphite-derived GO while significantly reducing environmental footprint. But to fully unlock this potential, researchers must transition from descriptive case studies to critical, mechanism-driven investigations supported by quantitative evidence.

Several challenges must still be addressed before GO and FGO can be widely adopted at an industrial scale. More sustainable and scalable synthesis routes are required, along with improvements in catalyst stability. Addressing these issues will require continued optimization of functionalization methods, deeper mechanistic understanding, and closer integration between laboratory research and process engineering. By carefully selecting synthesis routes, justifying functionalization choices, and applying appropriate kinetic models, researchers can develop GO-based catalysts that are both high-performing and environmentally responsible. Overall, GO and FGO offer a promising platform for developing cleaner and more efficient catalytic technologies, with strong potential to contribute to more sustainable chemical processes in the future.

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DECLARATION OF COMPETING INTEREST

None.

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