Exploiting Graphene Modified Metal Based Nano-Catalysts for Commercially Important Organic Transformations/Reactions: A Critical Review

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Abstract: *The selective oxidation of alcohols to carbonyl compounds represents one of the most fundamental and commercially significant transformations in synthetic organic chemistry. Aromatic aldehydes and ketones serve as indispensable building blocks across pharmaceutical, agrochemical, fine chemical, and materials science industries. Traditional oxidation methodologies relying on stoichiometric oxidants such as Dess–Martin periodinane, pyridinium chlorochromate (PCC), potassium permanganate, and dichromate, while synthetically well-established, suffer from severe drawbacks including the generation of toxic heavy metal waste and stoichiometric by-products. The imperative for sustainable chemistry has catalysed extensive research toward catalytic systems utilising molecular oxygen as the primary, environmentally benign oxidant. In this context, graphene-based two-dimensional materials have emerged as transformative platforms for heterogeneous catalysis. The single-layered graphene structure provides an exceptional support with an ultra-high specific surface area, tunable electronic properties, and the capacity for strong metal–support interactions. This critical review comprehensively evaluates the current state of graphene-modified metal-based nanocatalysts for commercially important organic transformations. We systematically examine the synthesis, characterisation, and catalytic applications of graphene-supported metal nanoparticles, with particular emphasis on alcohol oxidation, C–C bond forming reactions (Suzuki–Miyaura, Heck, Sonogashira), and reductions of environmental pollutants such as polyaromatic hydrocarbons. The critical roles of defects, doping, and functionalisation in modulating catalytic performance are analysed in depth. A comparative assessment against conventional catalysts and homogeneous counterparts is presented, alongside a discussion of mechanistic pathways, recyclability, and scalability. Key research gaps are identified, including the need for rational catalyst design, mechanistic elucidation using in situ techniques, and translation to industrially relevant continuous-flow processes. The review concludes that graphene-modified metal nanocatalysts represent a paradigm shift in sustainable organic synthesis, offering unprecedented opportunities for green and economically viable chemical transformations.*

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Keywords: Graphene, Metal Nanoparticles, Nanocatalysts, Heterogeneous Catalysis, Alcohol Oxidation, Sustainable Chemistry, Defect Engineering, C–C Bond Formation, Suzuki Coupling, Environmental Remediation.

Introduction

Aromatic aldehydes and ketones constitute a class of compounds of paramount importance across diverse fields including biological, pharmaceutical, chemical, and materials sciences [1–5]. These carbonyl compounds serve as essential intermediates in the synthesis of pharmaceuticals, agrochemicals, fragrances, dyes, and functional materials. The global market for aromatic aldehydes continues to expand, driven by increasing demand in fine chemical synthesis and pharmaceutical manufacturing. Consequently, the development of highly selective, efficient, and environmentally benign methodologies for the preparation of aromatic carbonyl compounds represents a central objective in modern synthetic chemistry [6,7].

Several synthetic routes exist for the preparation of aromatic aldehydes or ketones, including Friedel–Crafts acylation [8,9], ozonolysis of alkenes [10–12], hydration of alkynes [13–15], partial reduction of carboxylic acid derivatives [16,17], and the oxidation of alcohols [18,19]. Among these approaches, the oxidation of alcohols stands as the most important and widely employed method, primarily owing to the ready availability and structural diversity of alcohol substrates.

Historically, alcohol oxidation has relied upon stoichiometric oxidising reagents such as Dess–Martin periodinane [20,21], pyridinium chlorochromate (PCC) [22], potassium permanganate ($KMnO_4$) [23], potassium dichromate ($K_2Cr_2O_7$) and chromium trioxide (CrO_3) [24,25]. While these methods are well-developed and reliable, they suffer from fundamental limitations: the use of stoichiometric quantities of oxidants generates substantial amounts of toxic by-products, including heavy metal waste and organic residues, raising significant environmental and economic concerns. The imperative for sustainable chemical practices has therefore driven tremendous efforts toward the design of catalytic systems that employ molecular oxygen (O_2) as the primary, atom-economical, and environmentally benign oxidant for the selective oxidation of benzyl alcohols to benzaldehydes [26–30].

The emergence of graphene-based two-dimensional (2D) atomic materials has revolutionised the field of heterogeneous catalysis over the past decade [31–34]. Graphene's single-layered structure, comprising sp^2-hybridised carbon atoms arranged in a honeycomb lattice, provides a uniform platform with an exceptionally large specific surface area. This structure offers abundant binding sites for substrate interactions and/or active metal anchoring, while the extended π-conjugation system facilitates strong π–π interlayer interactions conducive to electrical or energy transfer [35,36]. These unique properties have prompted extensive exploration of graphene in diverse applications including catalysis [37–43], biosensing [44–48], supercapacitors [49–51], and lithium-ion batteries [52,53].

By inducing defects on graphene, its catalytic properties and the stability of metal–support binding are enhanced; controlling the defect formation mechanism is imperative to improve the catalytic potential [54–63]. Defects allow the active metal catalyst more direct access to graphene's electronic "highway," which can be tuned to modify the electron donor/acceptor property [64]. This is attributed to the bond formed between the metal particle at the defect site. Modified graphene inherently has a different band structure compared to pristine graphene. For defective graphene, the modifications are the inherent defects which change how electrons move through the π-network. The type of defect, functional group, and dopant control or direct the band structure and ultimately change the band gap. When metal atoms land on the surface of graphene oxide, the functional groups of the graphene oxide interact with metal atoms to form a graphene–oxide complex with a nanostructure. Because of the weak interactions, some donor atoms could depart from the metal centres to generate open coordination sites on metals for catalysis. Consequently, the graphene oxide–metal complex may act as a molecular switch accepting substrates and promoting the catalysis.

Though a large number of organic transformations have been carried out using metal nanoparticles, only few such studies have been carried out using graphene modified metal based nano-catalysts. The field therefore needs to be further explored.

This critical review aims to provide a comprehensive and systematic evaluation of graphene-modified metal-based nanocatalysts for commercially important organic transformations. The review encompasses: (i) synthesis and characterisation strategies for graphene-supported metal nanocatalysts; (ii) catalytic applications in alcohol oxidation, C–C bond formation (Suzuki–Miyaura, Heck, Sonogashira), reduction reactions, and transformations of environmental pollutants; (iii) the critical roles of defects, doping, and functionalisation in modulating catalytic performance; (iv) mechanistic insights into graphene-enhanced catalysis; (v) comparative assessment with conventional catalytic systems; (vi) identification of research gaps; and (vii) future directions for the field.

Graphene and Graphene Oxide: Structural Features and Properties

Structural Characteristics of Graphene

Graphene consists of a single atomic layer of sp^2-hybridised carbon atoms arranged in a two-dimensional honeycomb lattice [31]. This structure endows graphene with exceptional properties: an ultra-high theoretical specific surface area (≈2630 m^2/g), remarkable mechanical strength, outstanding electrical conductivity, and excellent thermal stability. The extended π-conjugation system facilitates efficient charge transport, while the basal plane and edges provide chemically distinct sites for functionalisation and metal anchoring [32,33].

Graphene Oxide and Reduced Graphene Oxide

Graphene oxide (GO) represents a chemically modified form of graphene bearing oxygen-containing functional groups including hydroxyl, epoxide, carbonyl, and carboxyl groups distributed across the basal plane and edges [34]. These functional groups render GO hydrophilic and readily dispersible in aqueous media, while also providing anchoring sites for

metal nanoparticle deposition. The presence of oxygen functionalities enables further chemical modification and facilitates strong metal–support interactions [35].

Reduced graphene oxide (rGO), obtained through chemical, thermal, or electrochemical reduction of GO, partially restores the conjugated sp^2 network while retaining some oxygen functionalities. rGO exhibits improved electrical conductivity compared to GO while maintaining sufficient functional groups for metal anchoring, making it an attractive support for catalytic applications [36].

Defects in Graphene: Types and Formation

Defects in graphene can be categorised into several types: (i) point defects including vacancies (monovacancies and divacancies), Stone–Wales defects, and substitutional dopants; (ii) line defects such as grain boundaries; and (iii) edge defects at the periphery of graphene sheets [31]. These defects can be intentionally introduced through various strategies including plasma treatment, ion bombardment, chemical etching, and thermal annealing [33].

The controlled introduction of defects is imperative for enhancing catalytic potential. Defects allow the active metal catalyst more direct access to graphene's electronic "highway," which can be tuned to modify the electron donor/acceptor properties [64]. This is attributed to the bond formed between the metal particle at the defect site. Various graphene modification methods have been discussed including using dopants and defects, decoration with metal/metal oxide nanoparticles [54–63].

The type of defect, functional group, and dopant control or direct the band structure and ultimately change the band gap. When metal atoms land on the surface of graphene oxide, the functional groups of the graphene oxide interact with metal atoms to form a graphene–oxide complex with a nanostructure. Because of the weak interactions, some donor atoms could depart from the metal centres to generate open coordination sites on metals for catalysis [64].

Synthesis and Characterisation of Graphene-Modified Metal Nanocatalysts
Synthesis Strategies

In Situ Reduction Method

The in-situ reduction method involves the simultaneous reduction of metal precursors and graphene oxide in a single step. Metal salts are dissolved in a GO dispersion, and a reducing agent is added to effect the reduction of both the metal ions and GO. Common reducing agents include sodium borohydride, hydrazine, and ascorbic acid. This approach yields well-dispersed metal nanoparticles anchored on the rGO surface [37–40].

Pre-formed Nanoparticle Deposition

In this approach, pre-synthesised metal nanoparticles are deposited onto the graphene or GO support through electrostatic interactions, covalent bonding, or physical adsorption. The pre-formed nanoparticles can be size-controlled and surface-modified prior to deposition, offering greater control over nanoparticle characteristics [41,42].

Solvothermal/Hydrothermal Synthesis
Solvothermal and hydrothermal methods involve heating a mixture of metal precursors and GO in a sealed vessel at elevated temperatures and pressures. These conditions promote the reduction of GO and the formation of metal nanoparticles with controlled size and morphology. The method is versatile and scalable, enabling the synthesis of various graphene–metal nanocomposites [43,44].

Microwave-Assisted Synthesis
Microwave irradiation provides rapid and uniform heating, enabling fast nucleation and growth of metal nanoparticles on graphene supports. This approach offers advantages including short reaction times, energy efficiency, and the ability to achieve small and uniform nanoparticle sizes [45].

Characterisation Techniques
Microscopic Techniques
Transmission Electron Microscopy (TEM): TEM provides direct visualisation of metal nanoparticle size, morphology, and distribution on the graphene support. High-resolution TEM (HRTEM) reveals lattice fringes and crystallinity of the nanoparticles [37,38].

Scanning Electron Microscopy (SEM): SEM offers information on the overall morphology and surface structure of the nanocomposite, complementing TEM analysis [39].

Spectroscopic Techniques
X-ray Diffraction (XRD): XRD confirms the crystalline nature of metal nanoparticles and the reduction of GO to rGO, as evidenced by the characteristic (002) peak shift [40].

X-ray Photoelectron Spectroscopy (XPS): XPS provides information on the oxidation states of metals and the surface chemical composition, including the presence of oxygen functionalities on GO/rGO [41].

Fourier Transform Infrared Spectroscopy (FTIR): FTIR identifies functional groups on GO and their modification upon metal deposition and reduction [42].

Raman Spectroscopy: Raman spectroscopy is particularly valuable for characterising graphene-based materials. The D band (defect-induced) and G band (graphitic) intensities provide information on the defect density and degree of graphitisation. An increased D/G ratio indicates successful reduction of GO and the introduction of defects [43].

Surface Area and Porosity Analysis
Brunauer–Emmett–Teller (BET) surface area analysis quantifies the specific surface area of the nanocomposite, which is critical for catalytic performance [44].

Catalytic Applications of Graphene-Modified Metal Nanocatalysts

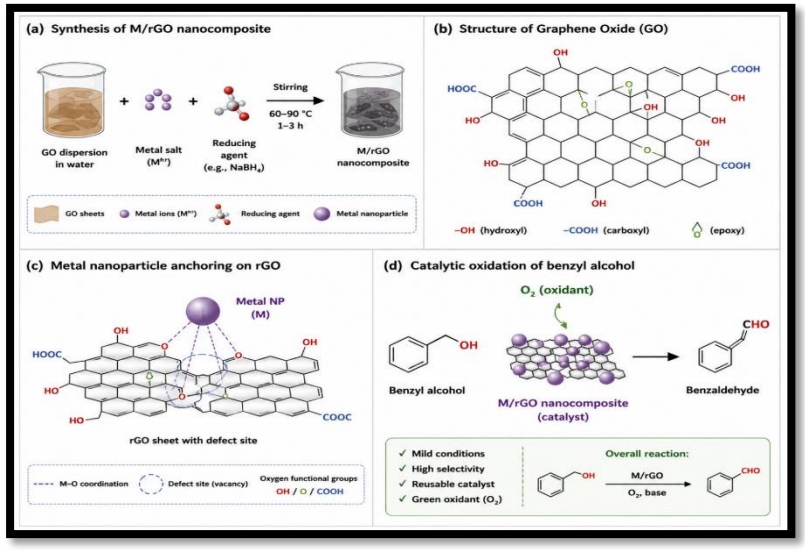
Oxidation of Alcohols

The selective oxidation of alcohols to carbonyl compounds represents one of the most extensively studied applications of graphene-modified metal nanocatalysts. The use of molecular oxygen as the terminal oxidant aligns with the principles of green chemistry, offering atom economy and minimising waste generation [26–30].

Graphene-supported noble metal nanoparticles, particularly gold, palladium, and platinum, have demonstrated exceptional activity and selectivity for alcohol oxidation. Gold nanoparticles supported on TiO_2 and reduced graphene oxide have been introduced as a new efficient aerobic oxidation photocatalyst for the oxidation of alcohols and alkylarenes, achieving 76–92% yield within 12 hours. Gold nanoparticles on α-hydroxy amide-functionalised graphene oxide have been developed for the environmentally benign oxidation of primary and secondary alcohols.

Ultrafine platinum nanoparticles stabilised on $Ti_3C_2T_x$/reduced graphene oxide nanocomposites have been employed for alcohol oxidation reactions, demonstrating enhanced electrocatalytic activity. ZnO–$MnCO_3$/N-doped graphene nanocomposites have been fabricated as efficacious and recoverable catalysts for selective aerobic dehydrogenation of alcohols under alkali-free conditions.

The enhanced catalytic activity of graphene-supported metal nanoparticles for alcohol oxidation is attributed to several factors: (i) the high surface area of graphene provides excellent dispersion of metal nanoparticles; (ii) strong metal–support interactions modify the electronic properties of the metal; (iii) the graphene support facilitates electron transfer; and (iv) defects and functional groups on graphene create anchoring sites and modulate catalytic activity.



C–C Bond Forming Reactions

Graphene-modified metal nanocatalysts have been extensively explored for C–C bond forming reactions, which are fundamental transformations in organic synthesis. The use of graphene as a support for transition metal-based catalysts in reactions involving the functionalisation of carbon–hydrogen bonds has been reviewed [65,66]. In many cases, the catalytic activities reported are comparable or better than the homogeneous counterparts, a feature which adds to a substantial degree of recyclability of the materials.

Suzuki–Miyaura Cross-Coupling

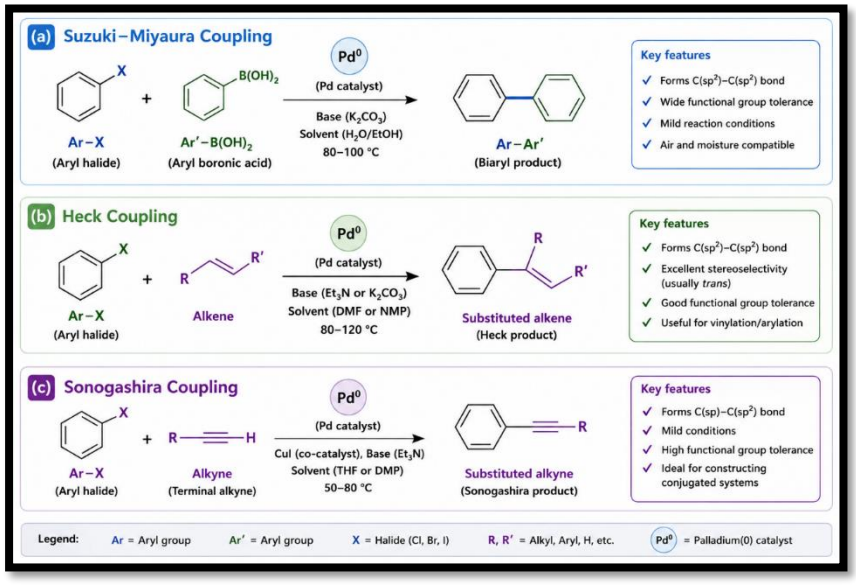
The Suzuki–Miyaura cross-coupling reaction, involving the coupling of aryl halides with arylboronic acids, is one of the most powerful methods for biaryl synthesis [64]. Palladium nanoparticles supported on graphene derivatives have demonstrated excellent catalytic activity for this transformation. The graphene support enhances catalyst stability and reusability while maintaining high activity.

Heck and Sonogashira Reactions

Graphene-supported palladium catalysts have also been applied to Heck and Sonogashira reactions, which involve the coupling of alkenes or alkynes with aryl halides. The high surface area and electron-donating properties of graphene contribute to enhanced catalytic activity and selectivity.

Carbon–Carbon Bond Formation via Carbocatalysis

Graphene and its derivatives have been introduced as metal-free carbocatalysts for C–C bond-forming reactions [68], offering an alternative to transition metal catalysis. Graphene-based materials have significant potential in metal-free catalysis because of the fine-tunable potential of the structure, high stability and durability, and no metal contamination, making them next-generation candidate materials in catalysis.



Reduction Reactions

Reduction of Nitroarenes

The reduction of nitroarenes to anilines is an important transformation in the synthesis of pharmaceuticals, dyes, and agrochemicals. Bimetallic and trimetallic nanoparticles supported on graphene have been developed as novel heterogeneous catalysts for the reduction of nitroarenes. These catalysts offer advantages including high activity, selectivity, and reusability.

Reduction of Carbonyl Compounds

Graphene-supported metal nanocatalysts have been employed for the reduction of aromatic aldehydes and ketones to alcohols. The combination of metal nanoparticles with graphene provides enhanced catalytic activity and selectivity compared to unsupported metal nanoparticles.

Multicomponent Reactions

Graphene oxide metal composites have been employed as catalysts for multicomponent reactions, which offer atom economy and synthetic efficiency [65]. These reactions include the synthesis of heterocyclic compounds, where the graphene support enhances catalyst stability and reusability.

Transformations of Environmental Pollutants

The reduction of polyaromatic hydrocarbons and other compounds of environmental concern can be performed using graphene-modified metal-based nanocatalysts. The high surface area and strong adsorption capacity of graphene facilitate the preconcentration and subsequent transformation of pollutants. Graphene oxide-based noble-metal nanoparticle composites have been developed for environmental applications [37].

The Role of Defects in Graphene-Enhanced Catalysis

Defect Engineering for Enhanced Catalytic Activity

The deliberate introduction of defects into graphene is a powerful strategy for enhancing catalytic performance. Defects allow the active metal catalyst more direct access to graphene's electronic "highway," which can be tuned to modify the electron donor/acceptor properties [64]. This is attributed to the bond formed between the metal particle at the defect site.

Various studies have demonstrated the role of defects in catalytic activity. The effect of defects on the catalytic activity of single Au atoms supported on carbon nanotubes and the reaction mechanism for CO oxidation has been investigated [58]. The intrinsic catalytic activity of graphene defects for the $Co(II/III)(bpy)_3$ dye-sensitised solar cell redox mediator has been demonstrated [59]. Catalytic activities have been shown to be enhanced by abundant structural defects and balanced N distribution of N-doped graphene in oxygen reduction reactions [60]. The role of lattice defects in catalytic activities of graphene clusters for fuel cells has been explored [61].

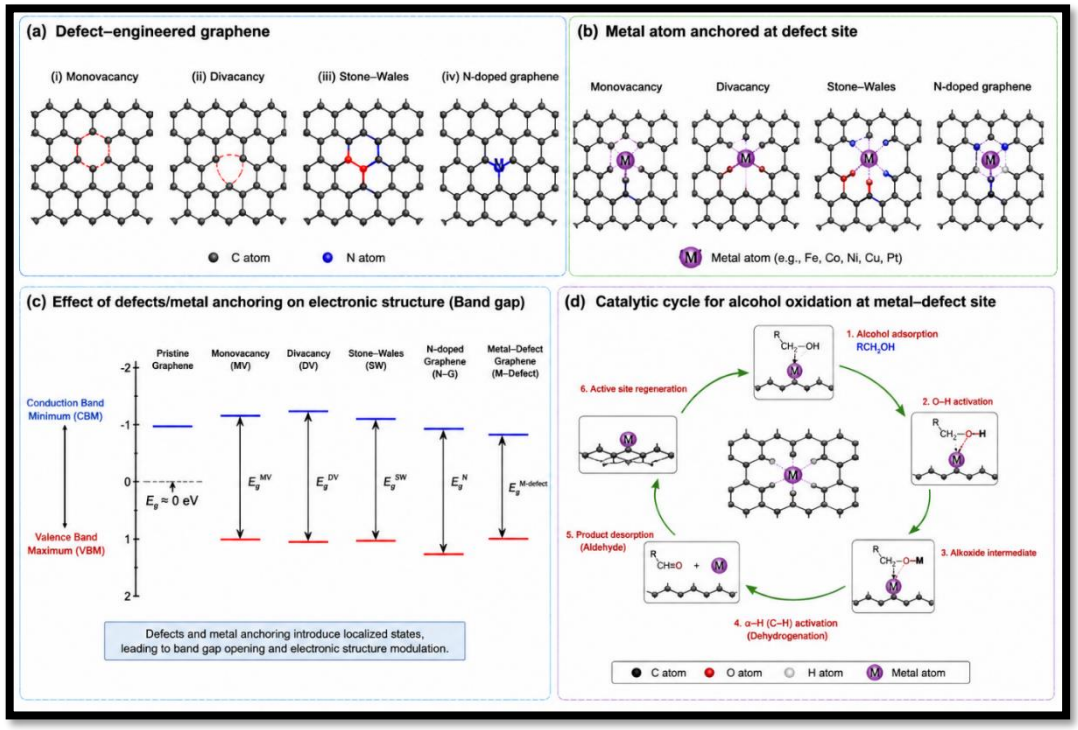
Doping and Functionalisation

Doping graphene with heteroatoms such as nitrogen, boron, sulfur, and phosphorus provides an additional means of modulating catalytic properties [62,63]. N-doped graphene, in particular, has been extensively studied for its enhanced catalytic activity in various reactions. The type of defect, functional group, and dopant control or direct the band structure and ultimately change the band gap [64].

Metal–Support Interactions

The interaction between metal nanoparticles and the graphene support plays a crucial role in determining catalytic performance. Strong metal–support interactions can modify the electronic structure of the metal, enhance stability, and promote electron transfer. When metal atoms land on the surface of graphene oxide, the functional groups of the graphene oxide interact with metal atoms to form a graphene–oxide complex with a nanostructure.

The support plays an important role for supported metal catalysts. Metal species such as nanoparticles, clusters, or single atoms can be deposited on carbon materials for various catalytic reactions [64].



Mechanistic Insights

Mechanisms of Alcohol Oxidation

The oxidation of alcohols on graphene-supported metal nanoparticles typically proceeds through a dehydrogenation pathway. The alcohol adsorbs on the metal surface, undergoes C–H bond cleavage to form an alkoxide intermediate, and subsequent β-hydride elimination yields

the carbonyl product. The graphene support can participate in the catalytic cycle through electron transfer and stabilisation of intermediates [26–28].

For aerobic oxidation, molecular oxygen is activated on the metal surface or at the metal–support interface, generating reactive oxygen species that facilitate the oxidation process. The high conductivity of graphene promotes electron transfer between the metal and the support, enhancing catalytic activity [29,30].

Mechanisms of C–C Bond Formation

In cross-coupling reactions, the graphene-supported metal catalyst facilitates the oxidative addition of the aryl halide, transmetallation with the coupling partner, and reductive elimination to form the C–C bond. The graphene support can stabilise the metal in different oxidation states and facilitate the catalytic cycle [64].

Role of Defects in Catalytic Mechanisms

Defects in graphene can act as active sites for catalysis, either directly or through the stabilisation of metal nanoparticles. The altered electronic structure at defect sites can promote adsorption of reactants, activation of substrates, and electron transfer processes [58–63].

Critical Analysis and Comparative Evaluation

Advantages of Graphene-Modified Metal Nanocatalysts

Graphene-modified metal nanocatalysts offer several compelling advantages over conventional catalysts:

High Surface Area: The ultra-high specific surface area of graphene provides excellent dispersion of metal nanoparticles, maximising the number of accessible active sites.

Enhanced Stability: Strong metal–support interactions and the robust nature of graphene enhance catalyst stability and resistance to sintering.

Superior Recyclability: Graphene-supported catalysts can be readily recovered and reused with minimal loss of activity.

Tuneable Properties: The properties of graphene can be modified through defect engineering, doping, and functionalisation to optimise catalytic performance.

Green Chemistry: The use of molecular oxygen as the oxidant and the heterogeneous nature of the catalyst align with green chemistry principles.

Comparison with Homogeneous Catalysts

Graphene-supported metal nanocatalysts offer significant advantages over homogeneous catalysts:

Ease of Separation: Heterogeneous catalysts can be readily separated from the reaction mixture by filtration or centrifugation, eliminating the need for costly separation processes.

Recyclability: While homogeneous catalysts are often difficult to recover and reuse, graphene-supported catalysts can be recycled multiple times.

Reduced Metal Leaching: Strong metal–support interactions minimise metal leaching into the product.

Comparable or Better Activity: In many cases, the catalytic activities reported are comparable or better than the homogeneous counterparts [65,66].

Comparison with Conventional Heterogeneous Catalysts

Compared to conventional heterogeneous catalysts such as metal oxides and zeolites, graphene-supported metal nanocatalysts offer:

Higher Surface Area: The ultra-high surface area of graphene exceeds that of conventional supports.

Superior Electrical Conductivity: The excellent electrical conductivity of graphene facilitates electron transfer in catalytic processes.

Tuneable Surface Chemistry: The ability to introduce defects, dopants, and functional groups provides greater flexibility in catalyst design.

Limitations and Challenges

Despite these advantages, several limitations and challenges remain:

Scalability: The large-scale production of high-quality graphene and graphene–metal nanocomposites remains a challenge.

Cost: The synthesis of graphene and the use of noble metals can be expensive.

Long-term Stability: The long-term stability of graphene-supported catalysts under industrial conditions requires further investigation.

Mechanistic Understanding: The mechanisms of catalysis on graphene-supported metal nanoparticles are not fully understood, particularly the role of defects and metal–support interactions.

Research Gaps and Future Directions

Fundamental Understanding

Mechanistic Elucidation: The mechanisms of catalysis on graphene-supported metal nanoparticles, particularly the roles of defects, metal–support interactions, and the graphene–metal interface, require further elucidation using in situ characterisation techniques.

Structure–Activity Relationships: Systematic studies of the relationships between catalyst structure (metal size, morphology, support properties) and catalytic activity are needed to guide rational catalyst design.

In Situ Characterisation: Advanced in situ characterisation techniques are needed to observe catalytic processes under reaction conditions.

Catalyst Design

Defect Engineering: Controlled introduction of specific defect types with predictable effects on catalytic performance requires further development.

Doping Strategies: Systematic investigation of the effects of different dopants and doping levels on catalytic activity and selectivity.

Bimetallic and Multimetallic Systems: The development of bimetallic and multimetallic nanoparticles on graphene supports offers opportunities for enhanced catalytic performance and reduced noble metal content.

Single-Atom Catalysts: Graphene-supported single-atom catalysts represent the ultimate in metal utilisation efficiency and offer unique catalytic properties.

Process Development

Scalable Synthesis: Development of scalable, cost-effective methods for the synthesis of high-quality graphene–metal nanocomposites.

Continuous-Flow Reactors: Translation of batch reactions to continuous-flow processes for industrial applications.

Reaction Optimisation: Systematic optimisation of reaction conditions for specific transformations.

Environmental Applications

Pollutant Degradation: Extension of graphene-modified metal nanocatalysts to the degradation of emerging environmental pollutants.

Sustainable Chemistry: Integration of graphene-based catalysts into sustainable chemical processes.

Scope and Deliverables

Immediate Research Scope

The immediate research scope for graphene-modified metal nanocatalysts encompasses several interconnected objectives. The preparation of various graphene-modified metal-based nanomaterials and their characterisation using NMR, SEM, TEM, UV-Visible spectroscopy, and FTIR represents a foundational objective. The focus would be on modifications of existing metal-based nanocatalysts to extend their applicability toward various catalytic properties.

The catalytic activities of formulated nanocatalysts would be analysed toward various commercially important organic reactions like reduction of aromatic aldehydes and ketones, Aldol condensation, Knoevenagel condensation, etc.

Extended Applications

The reduction of polyaromatic hydrocarbons and other compounds of environmental concern would be performed using graphene-modified metal-based nanocatalysts. The principles developed for these transformations can be extended to other classes of environmental pollutants.

Expected Deliverables

The expected deliverables include the development of efficient, recyclable, and environmentally benign catalysts for commercially important organic transformations. The elucidation of design principles for optimising graphene–metal nanocatalysts provides guidance for future development.

Conclusion

The past decade has witnessed remarkable progress in the development of graphene-modified metal-based nanocatalysts for commercially important organic transformations. The unique properties of graphene—its ultra-high specific surface area, exceptional electrical conductivity, tuneable surface chemistry, and capacity for strong metal–support interactions—make it an ideal platform for heterogeneous catalysis.

Graphene-supported metal nanoparticles have demonstrated exceptional catalytic activity and selectivity for alcohol oxidation using molecular oxygen as the green oxidant. These catalysts have also proven effective for C–C bond forming reactions including Suzuki–Miyaura, Heck, and Sonogashira couplings. The introduction of defects, doping, and functionalisation provides powerful strategies for modulating catalytic performance.

The catalytic activities reported for graphene-supported metal catalysts are often comparable or better than homogeneous counterparts, with the added advantages of ease of separation, recyclability, and reduced metal leaching. These features position graphene-modified metal nanocatalysts as promising candidates for sustainable chemical synthesis.

However, significant challenges remain. The scalable synthesis of high-quality graphene–metal nanocomposites, the long-term stability of these catalysts under industrial conditions, and the full elucidation of catalytic mechanisms require further investigation. The translation of laboratory-scale reactions to industrially relevant continuous-flow processes represents a critical step toward commercialisation.

The future of graphene-modified metal nanocatalysts lies in the integration of rational catalyst design, mechanistic understanding, and process development. The continued exploration of defect engineering, doping strategies, bimetallic systems, and single-atom catalysts will expand the scope and enhance the performance of these materials. The extension of these catalysts to the degradation of environmental pollutants and integration into sustainable chemical processes will contribute to the goals of green chemistry and environmental protection.

In conclusion, graphene-modified metal-based nanocatalysts represent a transformative approach to sustainable organic synthesis, offering unprecedented opportunities for efficient, selective, and environmentally benign chemical transformations. With continued research and development, these materials have the potential to significantly impact the chemical industry and contribute to a more sustainable future.

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