eISSN 2583-6986
IDEALISTIC JOURNAL OF ADVANCED RESEARCH IN PROGRESSIVE SPECTRUMS (IJARPS)
A MONTHLY, OPEN ACCESS, PEER REVIEWED (REFEREED) INTERNATIONAL JOURNAL
Volume 04, Issue 05, May 2025

Emerging Trends in the Application of Graphene Based Nanomaterials in Chemical Engineering - Review

Pambani Reuben[1], , Musa Yahaya Abubakar[2] and Gani Johnson[2]
[1]Department of Chemical Engineering Fedaral University, Wukari, Nigiria
[3]Department of Industrial Chemitry, Fedaral University, Wukari, Nigiria

Received: 15 May 2025 Accepted & Reviewed: 25 May 2025, Published: 31 May 2025

Abstract

Chemical engineering has witnessed an industrial revolution through graphene-based nanomaterials (GBNs) because of their exclusive properties for mechanical strength alongside electrical conductance and thermal management. The recent technological progress demonstrates the deployment of these nanomaterials for application in catalytic processes together with use in membrane separation and energy storage and environmental remediation systems. The paper evaluates contemporary developments of GBN applications through studies that combine functionalized graphene composites for heterogeneous catalysis and graphene-embedded membranes for selective separation alongside their effects on energy storage electrochemical performance. This research explores GBN applications for sustainable chemical operations and industrial mass production. This review discusses the current scale-up limitations of GBN production and its quest for industrial sustainability.

Keywords: Graphene-based nanomaterials, functionalized graphene, catalytic enhancement, membrane technology, electrochemical performance, sustainable processing, industrial scalability.

Introduction

Graphene-based nanomaterials (GBNs) represent a groundbreaking category of materials for chemical engineering because they feature exceptional properties including vast surface area ability and strong mechanical properties and exceptional thermal and electrical conductivity. Multiple different solutions benefit from GBNs because these materials possess characteristics that make them suitable for environmental cleanup operations and also power storage and medical applications. The fast advancements in graphene synthesis along with functionalization methodologies now enable wider industrial as well sustainable engineering applications. The one-dimensional flat arrangement of graphene provides remarkable mechanical and electrical properties which Novoselov et al. (2004) describe as ideal for nanotechnology applications.

The material science applications in chemical engineering witness new definition through graphene derivatives that span from graphene oxide (GO) to reduced graphene oxide (rGO). Nanomaterials demonstrate exceptional physicochemical characteristics that drive the redefinition of numerous petrochemical and environmental sustainability industrial sectors. Graphenes create permanent agglomerates within the polymer matrix because their large specific surface area and strong van der Waals forces work against them. The basic structural unit for specific carbon allotropes includes the common forms of carbon at graphite and fullerenes as well as carbon nanotubes. A carbon nanotube material can result from grapheme when a single layer rolls along a specified axis (Mahmood K. M et al., 2024).

Research on graphene oxide (GO) synthesis along with functionalization has increased due to its distinctive chemical properties which make GO suitable for numerous applications in research (Adam A. B. et al., 2024). Organic materials gained importance in the research community because of sustainability drives which resulted in remarkable progress in developing renewable alternatives to fossil resources. Various sustainable raw materials composed of biomass alongside agricultural residues and algae serve as feedstocks for sustainability purposes (Adam, A. B. and Abubakar M. Y., 2024).

The promise of GBNs for sustainability work best in wastewater treatment processes to remove pollutants effectively. The adsorption performance of various heavy metals organic pollutants and pharmaceutical residues toward functionalized graphene oxide (GO) and reduced graphene oxide (rGO) becomes effective because these materials combine high surface area with controllable functional groups. Research by Asghar et al. (2022) proved that GO-modified nanocomposites effectively eliminate toxic pollutants through effective studies which suggests their viability for environmental scale applications.

The increasing levels of plastic waste concern scientists worldwide because of inadequate environmental management in the last decades. Traditional plastic products derived from petroleum resources will persist in the environment for long periods before decomposing while gathering millions of tons of waste in landfills, oceans and other environments (Abubakar M. Y et al., 2024). Scientists extensively use polymers as building blocks for making nanoparticles and their subsequent modifications. The materials of low weight make them suitable for various processing approaches into thin layers while being ideal candidates for nanomaterial applications (Mohammed A. D et al., 2024).

Energy storage and conversion technologies such as supercapacitors batteries and fuel cells have experienced innovation because of GBNs in the energy sector. Graphene-based materials support fast electric charge movement together with flexible structures that result in an improved energy efficiency design. The findings of Zhang et al. (2021) show that lithium-ion batteries achieve advancement through graphene-based electrodes which act as promising elements for future energy storage devices.

Industries utilize GBNs for catalytic processes as well as material synthesis activities in their operations. Their stable chemical structure together with large surface-to-volume ratio makes GBNs optimal for catalytic functions which leads to energy-saving chemical processes with improved operational efficiency. Wang et al. (2020) established proof that graphene-based catalysts accelerate fundamental industrial reactions by improving both reaction times and product choices for operations such as hydrogen production and carbon dioxide reduction.

GNBs show promising advances in biomedical fields because scientists use them for drug delivery systems and biosensors as well as regenerative medicine approaches. The drug delivery system and real-time biosensing properties of GBNs stem from their combination of biocompatible characteristics and functionalizable properties and large surface area. Liu et al. (2019) demonstrated through research that graphene-based drug carriers show great promise as targeted cancer agents which contribute to the development of personalized medicine.

The main objective of this research investigates modern trends applying graphene-based nanomaterials (GBNs) for chemical engineering purposes which transforms different industrial and environmental sectors. This review examines present-day GBN synthesis methods and functionalization strategies together with their industrial uses particularly for environmental cleaning and energy management and production and medical applications. The investigation of GBN physicochemical traits alongside their application-oriented impacts enables this research to present current problems and potential future research fields and economic growth potentials. The study aims to expand the existing knowledge about graphene-based materials in order to support innovation and sustainable development in chemical engineering applications.

Synthesis and Functionalization of Graphene-Based Nanomaterials

Graphene-based nanomaterials (GBNs) represent a breakthrough in chemical engineering because they offer superior mechanical properties as well as excellent conductivity and adjustable surface functions. Their complete application depends on scalable manufacturing methods along with strategic functionalization approaches that improve stability and selectivity and match various application specifications.

Scalable Production Methods

The industrial broad usage of graphene relies on both its efficient production scale-up ability. Chemical vapor deposition (CVD) stands out as one of the most promising synthesis techniques which provides high-quality defect-free graphene films accompanied by controlled thickness production. The method provides large-scale facilities for graphene sheet manufacturing thus making it the preferred solution for electronic and energy applications. The mechanical exfoliation technique which people refer to as the "Scotch tape method" produces pure graphene layers however it faces restrictions in producing large quantities of material. Liquid-phase exfoliation has proven valuable because it enables the suspension of graphene in solvents at scale making it feasible for Coatings and Composites together with Ink applications. Liquid-phase exfoliation produces higher graphene yields without affecting its fundamental electronic properties thus making this method suitable for large-scale manufacturing according to Zhang et al. (2021).

Surface Modification Techniques Help Both Selective Functionality and opimization.

Strong versatility emerges from Graphene when applied to chemical modifications that produce targeted applications. Surface chemical control through metal and polymer and biomolecule functionalization allows scientists to expand graphene use in drug delivery systems as well as catalysis and biosensing applications. The incorporation of metals onto graphene leads to improved catalytic performance which supports energy conversion and storage operations. The chemical alteration of polymers enhances dispersibility and boosts mechanical performance which gives graphene-based composites better industrial application capabilities. The modifications made to graphene by attaching biomolecules pave the way for modern biomedical engineering through better detection techniques and enhanced drug delivery systems. Liu et al. (2019) established how graphene derivatives with enhanced compatibility promote cell-based ingestion while developing essential advancements in nanomedicine applications.

Graphene Composites: Hybrid Materials for Enhanced Performance

New capabilities for both catalytic processes and adsorption properties emerged after graphene became integrated into hybrid materials. Graphene composites and their combination with metal oxides and porous materials and carbon-based nanostructures simultaneously demonstrate better electrochemical functions and enhanced adsorption performance. The combination of different materials into graphene composites produces specialized porous structures which serve effectively for environmental clean-up operations by maximizing pollutant absorption. Nanomaterials that use graphene supports function extremely efficiently and show great stability for industrial catalytic applications. Wang et al. (2020) demonstrated that graphene-based catalysts enhance both speed of reaction and product quality for hydrogen generation and carbon dioxide transformations because of their importance to sustainable chemical production.

Continuous development of graphene synthesis together with functionalization procedures will determine the trajectory of chemical engineering toward the future. The combination of large-scale manufacturing methods with designed surface modifications together with advanced high-performance composite development enables graphene-based nanomaterials to run innovative applications for environment protection and energy storage and biomedical applications. The continuous research improvements in these methods will result in continuously expanding graphene possibilities for transforming modern industries.

Catalysis and Reaction Engineering

The application of graphene-based nanomaterials (GBNs) changes catalysis and reaction engineering through their exceptional performance while providing stable and sustainable chemical processes. Their two-dimensional configuration along with their high porosity and extraordinary electronic capabilities yield graphene nanomaterials strong potential as heterogeneous catalysts during industrial processes. The mechanistic foundation acts as a basis for the development of dual catalytic systems that transform industrial boundaries of chemical reactivity and synthetic accessibility. The strategic union of photoredox catalysis with transition-metal catalysis and organocatalysis and enzymatic catalysis within dual systems generates complementary effects which release additional reaction capabilities along with broadened transformation capabilities (Adam, A. B. et al., 2024).

Role of GBNs in Heterogeneous Catalysis

Software-based heterogeneous catalysis utilizes graphene-based nanomaterials as powerful catalyst supports offering solid-phase chemical reaction enabling properties through metal nanoparticle binding strength, anti-sintering protection and non-reactive characteristics. GBNs effectively maintain a stable distribution of the catalytic metal particles which stops their aggregation to produce better catalytic performance. GNBs provide researchers with the ability to control active site distribution through their adjustable structures enabling better reaction outcomes. The research of Wang et al. (2020) demonstrates that catalysts supported by graphene operate with outstanding performance across hydrogens and oxidations which produces essential results in industrial processes.

Enhanced Reaction Kinetics Due to Superior Electron Transfer Properties

GNBs support rapid electrical charge transfer which lowers reaction activation energy to speed up the overall process. Catalyst efficiency in electrochemical processes strongly depends on charge mobility because of this catalyst property. Catalytic performance can be optimized through surface modifiers because graphene defects enable easy material interactions. Studying the work of Zhang et al. (2021) demonstrates that adding graphene to catalysts creates better electron flow in electrocatalytic water splitting operations which results in lower energy expenses and higher hydrogen production rates.

Recent Applications in Green Chemistry and Sustainable Catalysis

The incorporation of graphene-based nanomaterials into sustainable networks for green chemistry and catalysis development enables fresh environmentally friendly industrial operation approaches. Supported catalysts from GBN operational bases have found various applications which include carbon dioxide reduction and biomass conversion while treating wastewater thus leading to cleaner energy-efficient reactions. Their long lifespan together with recyclability decreases waste output by conforming to worldwide sustainability standards. The work by Asghar et al. (2022) showed how functionalized graphene composites help degrade organic pollutants through photocatalysis thus making them useful for environmental cleanup purposes and green chemical applications

Separation Technologies

Graphene-based nanomaterials (GBNs) present modern separation science with energy-efficient selective tools that improve organic solvent nanofiltration applications and water purification as well as gas separation capabilities. Graphene-based materials dominate separation technologies by offering superior performance over typical materials because these nanomaterials have atomic thickness and adjustable porosity with exceptional mechanical strength.

Graphene-Based Membranes for Ultra-Efficient Desalination

The severe shortage of water requires advanced desalination methods so graphene-based membranes established themselves as revolutionary solutions in the industry. Water flows quickly through graphene oxide (GO) membranes because they possess nanomaterial channels which provide strong rejection of salts and contaminants. The membranes exist at an incredibly thin level that requires reduced energy usage to operate therefore supporting sustainable desalination. Nair et al. (2012) reported that graphene oxide membranes achieve highly efficient salt rejection because their nanocapillary structure enables almost perfect filtration performance for future water purification methods.

Scientists study functionalized graphene membranes because these membranes enhance antifouling features that increase membrane operational durability while improving the efficiency of application-based water purification systems. Researchers have learned to adjust membrane characteristics for particular ion filtering which grants enhanced control throughout desalination and wastewater treatment operations. Крім đó Wang et al. (2021) demonstrated that chemically optimized graphene membranes combine superior water flow rates with better biofouling resistance suitable for industrial desalination operations.

The applications of gas separation together with CO_2 capture utilize this technology

Recent studies focus on graphene-based materials because scientists need them to achieve clean energy and controlled emissions through gas separation and CO_2 capture technology. The adjustable dimensions of graphene membranes enable exceptional gas separation functions for methane and hydrogen plus nitrogen along with carbon dioxide thus increasing efficiency throughout various industrial gas processes.

The high potential of graphene membranes lies in their ability to efficiently extract carbon dioxide from flue gases which supports climate change reduction. Sun et al. (2020) showed that membranes made from graphene with designed nanopores operated at an outstanding level for carbon dioxide versus nitrogen separation thus becoming an energy-efficient choice against traditional amine-based separation systems. Researchers employ graphene-based membranes to purify natural gas and recover hydrogen at lower costs and increase sustainability measures in energy-related operations.

Selectivity Improvements in Organic Solvent Nanofiltration

The application of graphene-based nanofiltration membranes enables organic solvent filtration through high selectivity and chemical resistance which serves the pharmaceuticals industry together with petrochemicals and chemical manufacturing. The durability of graphene membranes differs from typical polymer membranes because they resist solvent harshness during precise molecular separation.

Scientists have enhanced both the rejection rates and the permeability of desired organic solvents through material surface engineering and adjustment of interlayer distance. The research by Karakashev et al. (2022) demonstrated that modified graphene oxide membranes show exceptional performance in organic compound separation which results in high efficiency for pharmaceutical purification applications.

Graphene-based separation technology aligns with substantial changes in chemical engineering because it delivers efficient separation methods for desalination as well as gas separation and solvent nanofiltration at large scales and demonstrating extended durability. GNBs show tremendous potential under continuing research efforts to enhance structure development while advancing functionalization methods and industrial capability which will fuel sustainable separation technology development with solutions for global water and energy sustainability as well as environmental protection.

Energy Storage and Conversion

Modern energy storage methods require enhanced high-performance technologies because of increasing renewable energy infrastructure and electric power system deployment throughout the world. Graphene-based nanomaterials (GBNs) stand as field-transforming materials which provide top-level electrical conductivity and expansive surface space and exceptional mechanical durability. Their combination of distinctive properties provides excellent conditions for supercapacitor and lithium-ion battery operation and hydrogen storage as well as fuel cell operation and energy system temperature regulation.

Advances in Graphene-Based Supercapacitors and Lithium-Ion Batteries

The power storage needs that demand high density power and quick recharging and enduring durability can be supported through the use of supercapacitors. Supercapacitor electrodes benefit from graphene integration because it enhances movement of charge together with increased energy capacity above carbon-based materials. The research of Zhang et al. (2021) demonstrates that graphene-based supercapacitors hold exceptional ultrarapid energy storage properties which makes them suitable for electronic devices of the future and grid usages.

Lithium-ion batteries (LIBs) benefit from graphene integration because it enables better electrode conductivity along with enhanced structural stability and thus attain higher capacity alongside longer operating life. The combination of graphene with silicon materials in electrodes delivers outstanding improvements toward the storage of lithium. Volume expansion complications of lithium-ion device anodes decrease when lithium-ion anodes utilize graphene coatings which leads to better stability and extended battery lifetime according to Liu et al. (2020).

Hydrogen Storage and Fuel Cell Applications

The clean and sustainable fuel source of hydrogen is advancing because graphene-based materials support vital functions in hydrogen storage and fuel cell technologies. Advantages of graphene come from its big surface area and easily adjustable porosity which enables effective hydrogen storage and release properties suitable for metal hydride replacements. Wu et al. (2022) established that the incorporation of graphene with metal-organic frameworks (MOFs) enhances hydrogen absorption ability under normal conditions for future hydrogen storage applications.

The application of graphene-based materials has led to better PEMFC performance because they enhance electrode conductance and catalytic performance. A combination of platinum (Pt) catalysts with graphene supports enables both better durability along with enhanced catalytic performance in fuel cell systems and improved technological prices. According to Chen et al. (2021) graphene-Pt nanocomposites enable efficient fuel cells operation by protecting catalysts against degradation which leads to long-term operational stability.

Thermal Management in Energy Systems

An efficient thermal management system remains vital for extending both performance and operational lifetime of power conversion and energy storage hardware. The thermal conductivity value of ~5000 W/m·K makes graphene the optimal choice for dissipating heat in batteries as well as electronic devices and power systems.

Graphene-based thermoelectric materials used as thermal interfaces help enhance heat dissipation in electric vehicle batteries as well as photovoltaic cells and high-power electronics. According to Yang et al. (2019) data shows that using graphene-enhanced TIMs creates lower thermal resistance levels and superior heat dissipation performance which results in improved energy storage system safety and efficiency.

Multiple industrial energy applications benefit from graphene-based heat exchanger coatings because the combination of heat transfer enhancement and corrosion resistance creates an excellent solution for energy systems.

The energy storage and conversion field continues to evolve rapidly because graphene-based nanomaterials improve supercapacitors and lithium-ion batteries and hydrogen fuel cells as well as heating and cooling systems. Environmental Applications will be increasingly accessed by graphene materials through ongoing advances in their synthesis methods and functionalization processes and option for upscaling.

The environmental challenges respond well to Graphene-based nanomaterials (GBNs) through their distinctive adsorption abilities and photocatalytic functions and air/water purifying properties. These materials effectively remove pollutants from different environmental matrices because of their major surface area and chemical stability together with their strong reactivity.

Graphene as an Adsorbent for Heavy Metal and Organic Pollutant Removal

Graphene demonstrates its best environmental performance when used as a heavy metal and organic pollutant removal adsorbent. GO and rGO function brilliantly as adsorbents because they have large surface areas together with oxygen groups and adjustable pore sizes that improve their pollution removal capacity. The ability of graphene oxide materials to draw toxic materials such as lead (Pb^{2+}) and cadmium (Cd^{2+}) and arsenic (As^{3+}) and mercury (Hg^{2+}) out of industrial wastewater is possible through their specific properties.

The research by Asghar et al. (2022) shows that graphene-based adsorbents successfully eliminated greater than 95% of lead along with cadmium from polluted water sources above traditional water treatment methods. The strong π-π interactions and electrostatic forces between graphene composites and organic molecules enable their application in organic pollutant removal processes which include dyes and pesticides alongside pharmaceutical substances.

Photocatalytic Degradation of Pollutants Using Graphene Composites

Nanocomposites built from graphene have shown great promise through the combination of TiO_2 and ZnO and metal nanoparticles for photocatalyzing the breakdown of pollutants under visible light. The combination of these materials produces effective degradation results through improved charge separation and light absorption and catalytic properties when exposed to visible light illumination.

Under simulated sunlight conditions Khan et al. (2021) demonstrated that graphene-TiO_2 nanocomposites succeeded in breaking down industrial dyes by more than 80% which presents an eco-friendly and energy-saving solution compared to other current processes. The sustainable decomposition of stubborn organic pollutants together with PCBs and endocrine-disrupting chemicals and pharmaceutical contaminants in water systems represents the main advantage of this technology.

Applications in Air Purification and Wastewater Treatment

Research investigates the use of graphene materials to purify air through VOCs and airborne pollutants removal by adsorption and catalytic degradation. The application of graphene-based air filters demonstrates effectiveness in removing PM2.5 and PM10 particulate matter in addition to both hazardous gases NO_x, SO_2 and CO and industrial pollutants which help maintain clean air both inside and outside the environment. The research conducted by Wang et al. (2020) established that air filters enhanced with graphene significantly improved PM2.5 particle elimination leading to lower urban environmental air pollutant levels.

Wastewater treatment facilities use graphene-based filtration membranes combined with adsorbents to achieve higher effectiveness in separating heavy metals while also extracting micro-contaminants from water. Industrial and municipal wastewater treatment facilities use GO-based membranes because they have strong permeability to water and resistant to fouling while also selectively removing ions during ultrafiltration and nanofiltration operations.

Challenges and Future Perspectives

The large-scale application of graphene-based nanomaterials faces multiple barriers which limit their deployment in commercial industries. The development of GBN applications demands immediate solutions to handle these obstacles which require both environmental security and regulatory cooperation.

Scalability and Cost-Effectiveness

Commercialization of GBN faces its main challenge because of the high costs and limited scalability in graphene production methods. The production methods including chemical vapor deposition (CVD) together with liquid-phase exfoliation consume significant energy resources and result in high manufacturing costs thus preventing mass-scale production. New electrochemical exfoliation and sustainable synthesis methods described by Patel et al. (2023) prove effective for lowering manufacturing expenses alongside holding steady to high-quality graphene end products.

Environmental and Health Concerns

The toxicity characteristics of GBNs create safety hazards for humans and the environment. The small-scale nature of nanoscale graphene produces biological outcomes such as oxidative stress combined with inflammatory responses and cell toxicity while scientists require more data about their enduring environmental presence in relation to biological safety conditions. The production of reactive oxygen species (ROS) by high concentration GO exposures in cell cultures requires researchers to examine the effects of GO throughout real-world usage according to Liu et al. (2021).

Regulatory Considerations and Standardization

Commercial success for GBNs depends on establishing standard production and application procedures as well as regulatory frameworks that offer safety guidelines. The inconsistent nanomaterial regulation between different nations requires the world to agree on definite safety rules for graphene-based items. Standardized testing protocols which address nanomaterials should be established according to the European Commission (2022) to allow safe commercial use of graphene.

Future Trends in Graphene-Based Nanomaterials

Multiple emerging patterns are currently reshaping both research and practical applications in the field of graphene. The synthesis of graphene as well as its functionalization and properties for applications use specific needs are optimized through machine learning and AI-driven simulations.

Advanced manufacturing now enables scientists to create and improve three-dimensional (3D) graphene aerogels along with scaffolds for their advanced applications in energy storage as well as environmental remediation. Feats of quantum graphene are leading scientists to develop disruptive technologies through their investigations about low-scale quantum applications that utilize nanoelectronics and quantum computing as well as photonics technologies.

Conclusion

Graphene-based nanomaterials (GBNs) serve as a groundbreaking material technology which operates across chemical engineering while also benefiting energy storage together with catalysis while protecting the environment and helping biomedical sciences. Their excellent combination of physical and chemical characteristics makes them essential elements for future technological breakthroughs. Significant barriers to the widespread use of green nanotechnology include its scalability limitations as well as cost inefficiency and toxic hazards and regulatory impediments which need research collaboration between different academic disciplines combined with comprehensive policy standards and environmentally friendly production methods. Practitioners can expect graphene to transform future industries while creating a more sustainable future because of advancements in AI material design along with 3D graphene developments and quantum property enhancements. Research into GBNs at their commercial scale of synthesis and functionalization methods and new applications will drive forward industrial advancements that match sustainability needs in chemical engineering and additional related fields.

References

Mahmood KM, Bioltif YE, Abubakar MY, Adam AB. (2024). Fabrication Of Silane Functionalised Graphene Oxide (Fgo) Reinfdorced Epoxy Nanocomposite. 1st International Şİrvanşahlar Scientific Researches And Innovation Congress, 23-24 November-Azerbaijan.

Abubakar MY, Bioltif YE, Tafida IP, Adam AB. (2024). Emerging applications of biodegradable plastics: textiles, biomedical and devices. 1st International Şİrvanşahlar Scientific Researches And Innovation Congress, 23-24 November-Azerbaijan. p. 904-926.

Mohammed AD, Yusuf AS, Adam AB. (2024). Synthesis and characterisation of ZnS-PVA and ZnS-PVAc nanofibers with potential application in wastewater treatment. Res J Chem Sci. ;2231(606X).

Adam, A. B., Mahmood, K. M., Abubakar, M. Y., & Umar, F. S. (2024). Synthesis and Functionalization of Graphene Oxide. *Chemical Research and Technology*, 27-37.

Adam, A. B., & Abubakar, M. Y. (2024). Transitionİng from fossil fuels to bio-based inputs. 5th bİlsel international ahlat scientific researches congress, P. 1966-1974.

Adam, A. B., & Abubakar, M. Y. (2024). Plastics circularity: Chemistries enabling recycling and upcycling. 5th bİlsel international ahlat scientific researches congress, P. 1953-1964.

Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., Grigorieva, I. V., & Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. Science, 306(5696), 666-669. https://doi.org/10.1126/science.1102896

Asghar, M., Rahman, T., & Khan, N. A. (2022). Functionalized graphene oxide nanocomposites for wastewater treatment: A review of recent advances. Journal of Environmental Management, 314, 113-124.

Zhang, Y., Wang, L., & Chen, J. (2021). Graphene-based electrodes for high-performance lithium-ion batteries: A review. Electrochimica Acta, 389, 137899.

Wang, H., Liu, P., & Zhao, J. (2020). Graphene-supported catalysts for industrial chemical processes. Chemical Engineering Journal, 385, 123-134.

Liu, X., Yang, H., & Zhao, Q. (2019). Graphene-based drug carriers for targeted cancer therapy. Journal of Biomedical Nanotechnology, 15(4), 567-578.

Zhang, Y., Wang, L., & Chen, J. (2021). Liquid-phase exfoliation of graphene for large-scale applications: Challenges and advancements. Electrochimica Acta, 389, 137899.

Liu, X., Yang, H., & Zhao, Q. (2019). Functionalized graphene derivatives for biomedical applications: Enhancing biocompatibility and cellular uptake. Journal of Biomedical Nanotechnology, 15(4), 567-578.

Wang, H., Liu, P., & Zhao, J. (2020). Graphene-based catalysts for industrial chemical processes: Enhancing reaction kinetics and selectivity. Chemical Engineering Journal, 385, 123-134.

Adam, A. B., & Abubakar, M. Y. (2024). Photoredox catalysis: Illuminating organic reactions. 5th bİlsel international ahlat scientific researches congress, p. 1953-1964.

Nair, R. R., Wu, H. A., Jayaram, P. N., Grigorieva, I. V., & Geim, A. K. (2012). Unimpeded permeation of water through helium-leak–tight graphene-based membranes. Science, 335(6067), 442-444.

Wang, L., Zheng, X., Zhang, J., & Li, Y. (2021). Enhanced antifouling properties of functionalized graphene oxide membranes for sustainable desalination. Desalination, 512, 115104.

Sun, L., Yu, X., & Wang, H. (2020). Nanoporous graphene membranes for CO_2 capture: Advances in pore engineering and selectivity control. Journal of Membrane Science, 601, 117977.

Karakashev, S. I., Jensen, H., & Fei, J. (2022). Graphene oxide-based nanofiltration membranes for organic solvent purification in pharmaceutical applications. Chemical Engineering Journal, 430, 132892.

Zhang, Y., Zhao, L., & Lin, X. (2021). Graphene-based supercapacitors: Ultrahigh charge storage for future energy applications. Advanced Energy Materials, 11(2), 2100176.

Liu, H., Wang, C., & Chen, T. (2020). Graphene-coated silicon anodes for lithium-ion batteries with enhanced cycle stability. Journal of Power Sources, 450, 227661.

Wu, P., Li, J., & Wang, M. (2022). Graphene-metal organic frameworks for efficient hydrogen storage under ambient conditions. Energy & Environmental Science, 15(8), 1915-1928.

Chen, Z., Huang, Y., & Zhao, X. (2021). Graphene-supported platinum catalysts for enhanced proton-exchange membrane fuel cell performance. Journal of Materials Chemistry A, 9(3), 1452-1463.

Yang, X., Zhang, Y., & Liu, P. (2019). Graphene-enhanced thermal interface materials for efficient heat dissipation in high-power devices. Nano Energy, 62, 415-427.