Review

A perspective on graphene-based material platforms for mitigating new contaminant

Junjie Chen[1], Yichi Zhang[1], Shirui Wang[1], Xing Liu[1], Chaoqi Ge[2], Lin Shi[2], Zetao Wang[2], Yongchun Wei[2*] and Guosheng Shi[1*]

Abstract

The increasing prevalence of new contaminants in the environment severely limits the efficacy of conventional pollution control technologies. Graphene and graphene-based materials show significant potential for the remediation of new contaminants due to their tailorable and versatile physicochemical characteristics. Here, recent advances in graphene-based platforms for treating new contaminants are systematically summarized, which are categorized here as newly identified emerging contaminants and radioactive species. The discussion focuses on two key applications: the current status of graphene-based membrane separation for removing both conventional and new contaminants, and progress in graphene-based catalytic systems for degrading contaminants in aquatic environments. Future efforts should therefore prioritize the rational design of mass-transfer nanochannels, the application of graphene membranes in contaminant preconcentration for detection, and the development of integrated separation-oxidation catalytic systems, collectively paving the way for next-generation water purification technologies.

Highlights

- New contaminants challenge conventional treatment and graphene offers solutions for their remediation.
- Recent advances in graphene-based membrane separation and catalytic degradation systems are critically reviewed.
- Perspectives: rational nanochannel design, membrane preconcentration and integrated separation-oxidation systems.

Graphical abstract

---
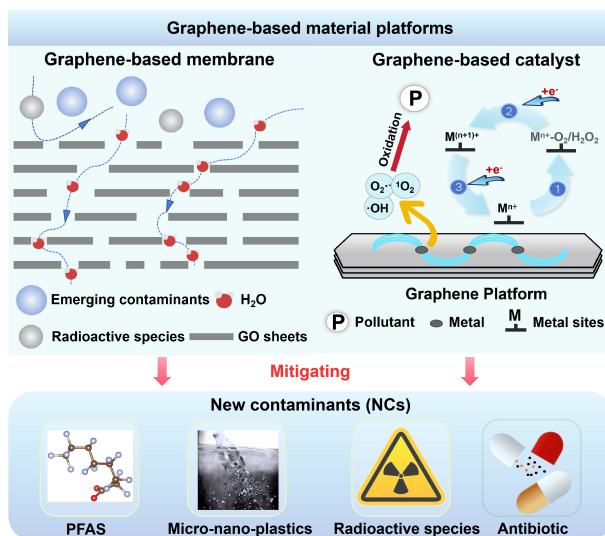
* Correspondence: Yongchun Wei (weiyongchun@cnsi.ltd); Guosheng Shi (gsshi@shu.edu.cn)

Full list of author information is available at the end of the article.

Introduction

New contaminants (NCs), as defined by international environmental and health agencies, refer to substances of emerging concern that are not yet adequately regulated or monitored under current frameworks, despite their potential risks to human and environmental health[1–4]. With the acceleration of industrialization and urbanization, the widespread presence of NCs in the environment has garnered significant global attention[5–8]. Specifically, NCs originate from a wide range of sources, including industrial sectors such as pharmaceuticals, fertilizers, personal care products, and the nuclear industry, as well as diverse chemical and consumer groups. Key contributors encompass pesticides, hormones, antibiotics, surfactants, antibacterial agents, per- and polyfluoroalkyl substances (PFAS), cleaning solvents, cosmetics, beauty formulations, and various packaged foods and beverages[9]. Several studies have reported that the concentration of NCs in wastewater typically ranges from ng L^{-1} to µg L^{-1} levels[10]. They are collectively defined by a suite of characteristics, including complex provenance, elevated toxic potency at trace concentrations, and pronounced environmental persistence and mobility, which fundamentally distinguish them from traditional pollutants[11–13].

The stark disparity between the approximately 500–1,000 contaminants regulated under existing frameworks and the proliferation of NCs, which remain largely undefined and unmonitored, has led to substantial socioeconomic and health burdens associated with unregulated NCs[1]. For example, PFAS, owing to their extreme environmental persistence and historically unregulated use, bioaccumulate in humans, and a substantial body of research links early-life exposure to deficits in key developmental domains, including cognition, language, motor skills, and socio-emotional performance[14]. The ability of plant leaves—a fundamental unit of the food chain—to directly absorb atmospheric micro-/nano-plastics poses a significant pathway for these particles to enter the food web; they have been detected in the human bloodstream and various tissues, consequently disrupting normal organ function[15]. Additionally, recent studies have found that the average microplastic (MP) abundance in marine fish was measured at 3.5 ± 0.8 particles per specimen, whereas in highly polluted waters, oysters exhibited the highest contamination level, reaching 99.9 particles per individual[16].

Moreover, radioisotope contamination represents a growing global nuisance, driven by the development of the nuclear industry[17]. Cesium-137 (^{137}Cs) from the Fukushima accident, with its 30.1-year half-life, represents a long-term threat to environmental and human health, primarily due to persistent contamination of agricultural systems. Furthermore, its classification as an NC does not stem from its novelty as a radioactive substance, but rather from the growing recognition of its risks and the regulatory challenges it presents—illustrating how NCs transcend traditional categories based on their emerging profile of concern[18]. While present at lower concentrations in Fukushima's wastewater, tritium also constitutes a potential long-term environmental hazard. As the prevalence of such NCs increases in the environment, they significantly impede the efficacy of conventional treatment technologies.

Graphene-based materials have garnered significant attention due to their tunable surface chemistry, high capacity, and multifunctional capabilities[19–23]. These properties position graphene-based materials as versatile solutions for environmental remediation, catalysis, and energy sectors, and they are equally critical for targeted applications in advanced water treatment membranes. Leveraging a research foundation built over decades, which confirms the remarkable effectiveness of graphene-based materials against traditional pollutants (e.g., heavy metals, dyes), substantial promise is anticipated for graphene-based membranes and catalytic technologies in addressing NCs. This perspective reviews the application of graphene-based membranes in the separation of NCs and the efficacy of graphene-based materials in catalytic degradation, proposing strategic avenues for future water treatment technologies.

A perspective is outlined that categorizes NCs as emerging contaminants and radioactive species, focusing on the progress of graphene-based membrane separation and catalytic platforms for their remediation (Fig. 1).

Graphene-based membranes: a strategic barrier against NCs

Graphene membranes demonstrate revolutionary advantages in water treatment, leveraging precise nanoscale pores and surface chemistry for exceptional efficiency and selectivity, while their atomic thinness enables high flux with minimal energy input[19]. Impermeable by nature, perfect monolayer graphene requires the deliberate introduction of nanopores to allow the transit of water, ions, and gases—a concept established in early theoretical research[24]. However, the experimental fabrication of large-area graphene sheets with uniform pore sizes remains a formidable challenge. Alternatively, graphene oxide (GO) nanosheets, known for their excellent dispersibility in various solvents and high aspect ratio, can be readily deposited onto porous substrates via spin-coating or vacuum filtration[19–21]. This process facilitates the formation of well-ordered laminates, making GO membranes highly effective for removing diverse contaminants. Excitingly, the structural versatility of graphene-based membranes gives rise to distinct transport paths, allowing their deployment in processes like pervaporation, reverse and forward osmosis, and opening new avenues for treating environmental pollutants[19].

To date, graphene-based membranes have shown great promise as an advanced barrier for the targeted removal of various contaminants. For conventional contaminants, the graphene-based membrane separation process based on the size exclusion effect of the two-dimensional nanochannels within the GO membrane has proven highly efficient and well-established for the removal of heavy metal ions and organic dyes. Techniques including thermal reduction[25], cross-linking[26], and intercalation[27] allow for the control over the interlayer spacing of GO membranes. Among them, thermal reduction offers procedural simplicity, but often leads to concomitant structural densification and the generation of uncontrolled defects. While the cross-linking approach significantly enhances the stability of GO membranes and allows for precise tuning of the interlayer spacing, the final d-spacing is inherently constrained by the molecular dimensions of the cross-linker employed. The intercalation method also enables precise interlayer control; however, the long-term operational stability is compromised by the gradual leaching of intercalants, resulting in performance attenuation. This leaching issue remains a pivotal bottleneck hindering the practical application of intercalated graphene-based membranes. For instance, the GO membrane cross-linked with amino acids achieved a water permeance of 191.0 L m^{-2} h^{-1} bar^{-1} and a high FeCl$_3$ rejection rate of 98.2%, alongside enhanced operational stability[26]. Meanwhile, recent studies reported that the reduced GO membranes treated by electron beam irradiation can be used for dye and heavy metal ion removal. Remarkably, the membranes exhibited ultrahigh water permeance, ranging from 92.7 to 267.1 L m^{-2} h^{-1} bar^{-1}, while simultaneously maintaining effective rejection rates for various dyes, as well as for multivalent
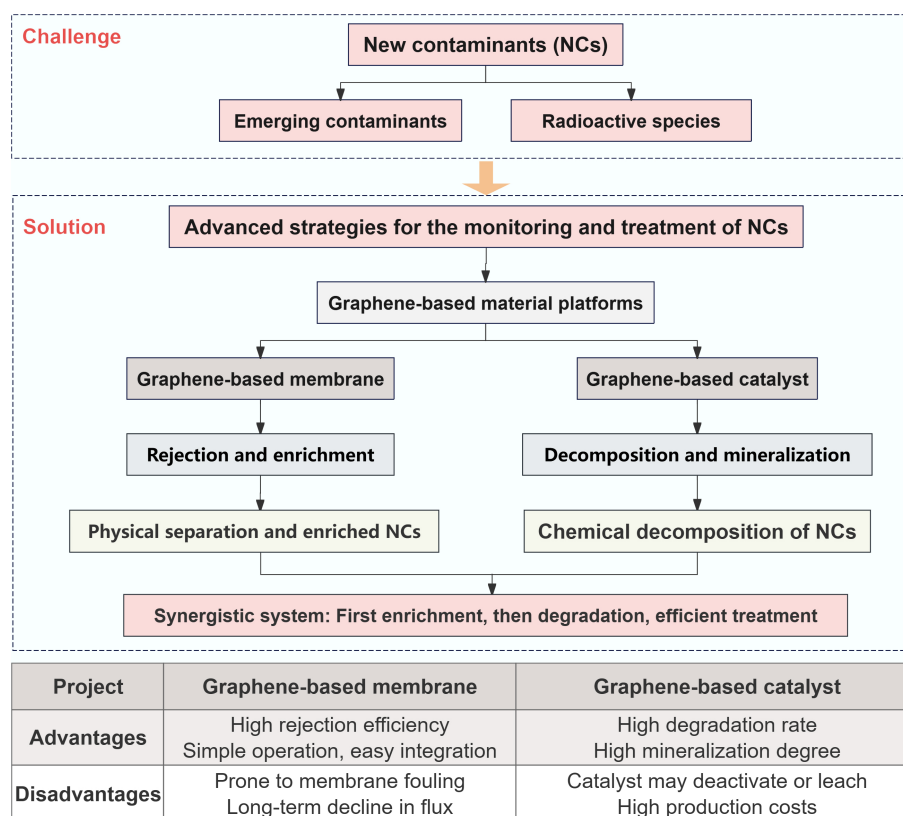
Fig. 1 Framework for graphene-based material platforms in the mitigation of NCs.

heavy metal ions[28]. Interestingly, further studies demonstrated that utilizing GO nanosheets of a smaller lateral size can significantly improve the membrane's separation performance. Notably, the optimal membrane exhibited a water permeance as high as 819.1 L m^{-2} h^{-1} bar^{-1}, coupled with a 99.7% rejection rate for FeCl$_3$, an outcome attributed to the shortened and less tortuous transport pathways that facilitate rapid water permeation[29].

Recently, the GO membranes have also demonstrated excellent separation performance for the NCs. Yan et al. reported a reduced GO membrane with short Z-type water transport for the MP removal (Fig. 2), which demonstrated an outstanding performance by simultaneously delivering a water permeance as high as 236.2 L m^{-2} h^{-1} bar^{-1} and an MP rejection rate of 99.9%[30]. Notably, the removal of PFAS from water has received significant attention as a critical environmental challenge. A β-cyclodextrin-modified GO (GO-βCD) membrane was designed to separate PFAS in surface water and groundwater, which showed a permeance of 21.7 L m^{-2} h^{-1} bar^{-1} with a retention of over 90%[31]. Theoretical calculations confirmed that the mass transfer of PFAS molecules encounters a significantly higher energy barrier in the GO-βCD membrane compared to the pristine GO membrane. Recent relevant studies on NC removal using GO membranes have been systematically reviewed, as summarized in Table 1.

Currently, reports on the application of graphene-based membranes for treating NCs in water remain relatively scarce. This scarcity can be attributed to several intertwined challenges. The separation mechanisms for NCs in real water matrices involve intricate synergy between electrostatic interactions, hydrophobic effects, π-π conjugation, and hydrogen bonding, which are difficult to deconvolute and engineer. Furthermore, laboratory performance

evaluations often fail to adequately simulate complex real-world conditions, creating a significant bench-to-application gap. Finally, the lack of scalable, reproducible fabrication and module integration techniques for graphene-based membranes further constrains both fundamental research and practical exploration.

On the other hand, the unique quantum effects and structural properties of graphene make it a promising candidate for the separation of radioactive species. Conventional processes for hydrogen isotope separation, such as cryogenic distillation, chemical exchange, centrifugation, thermal diffusion, and adsorption, are often plagued by high energy consumption and low efficiency. In this context, graphene-based membranes present a promising alternative for hydrogen isotope separation. Lozada-Hidalgo et al discovered that while atoms and molecules cannot permeate monolayer graphene, hydrogen ions can penetrate it[40]. Since deuterons experience a higher energy barrier than protons, their permeation through the graphene crystal is significantly slower. This phenomenon enables the development of a graphene-based electrochemical pump for hydrogen isotope separation, achieving a proton-deuteron separation factor of up to eight—far exceeding that of conventional cryogenic distillation (< 1.8)—while also being more energy-efficient, safe, and environmentally benign[41]. Recent studies also revealed that GO membranes assembled from nanosheets with lower oxidation degrees and larger lateral sizes exhibited both high rejection of deuterated water (HDO and D$_2$O) and high water permeance[42]. Furthermore, functionalized GO membranes have also exhibited potential for application in the enrichment of Cs$^+$ within complex aquatic systems[38].
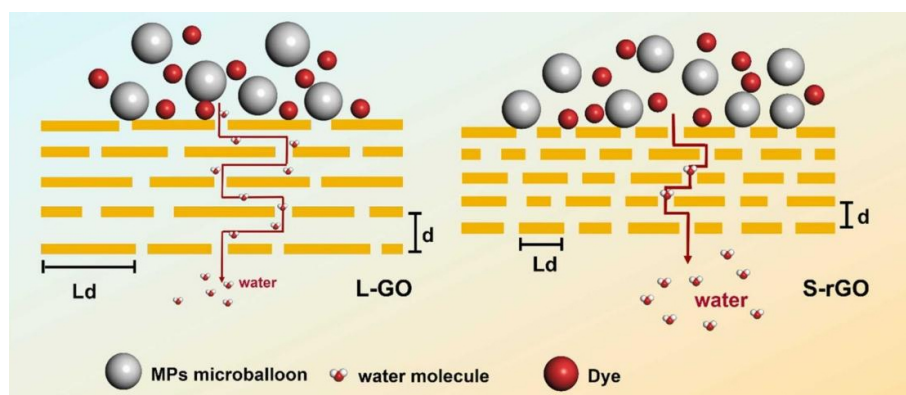
Fig. 2 Water transport pathways and rejection mechanisms of graphene-based membrane[30].

Catalytic conversion on graphene platforms: the path to destruction of NCs

Graphene-based membrane separation and graphene-derived catalytic degradation technologies serve complementary functions in the management of NCs. The former enables efficient enrichment and rejection of contaminants, facilitating their monitoring and subsequent advanced treatment. The latter promotes complete mineralization and elimination of contaminants, effectively preventing secondary pollution. By integrating these two approaches, a continuous technological framework is established from 'concentrative separation' to 'complete transformation', allowing for precise and comprehensive control throughout the entire contaminant management process.

Graphene-based materials possess unique properties such as ultra-high electron mobility, high specific surface area, high surface functional group density, and wide-spectrum absorption capacity, making them an ideal platform for catalytic degradation of pollutants[43–46]. Their two-dimensional structure not only facilitates the construction of efficient multi-heterojunctions but also significantly enhances the catalytic degradation efficiency by promoting interfacial charge separation and providing abundant adsorption sites, thereby achieving a synergistic effect. Graphene-based materials serve as versatile catalytic platforms, offering novel pathways for the remediation of NCs.

Previous studies have extensively investigated their application in degrading conventional dyes and other organic pollutants. Recently, a T-shaped Fe_2O_3@FeOCl@graphene composite catalyst was developed[47]. Based on the cation-π interaction between graphene and the metal precursor, this catalyst enables the confined growth of Fe_2O_3 nanosheets and the vertical assembly of FeOCl nanosheets. This unique configuration overcomes the traditional trade-offs among adsorption, activation, and desorption processes involving •OH radicals. As a result, the catalyst achieved a degradation conversion rate of 1.65×10^{-3} min^{-1} for bisphenol A, which is more than an order of magnitude higher than that of traditional materials. Furthermore, a graphene-controlled all-solid-state synthesis route was developed to construct atomically dispersed FeO_X alongside Fe_2O_3 nano-islands at low temperature, a structure tailored to enhance the three critical steps in peroxydisulfate-driven Fenton-like oxidation: reactant adsorption, O–O bond activation and reactive species desorption[48]. Meanwhile, the graphene material platform can also serve as a highly versatile platform in photocatalysis, demonstrating exceptional performance across a variety of reaction systems. The ZnO-reduced graphene oxide (ZnO-rGO) nanocomposites displayed a degradation efficiency of approximately 99% for high-concentration methylene blue (200 mg L^{-1}) within 60 min through the synergistic photogenerated charge separation and free radical oxidation pathways[49]. Compared with pure ZnO and rGO, the ZnO-rGO composite showed an improvement of 25% and 43%, respectively.

Owing to their high C–F bond energy and stability, NCs like PFAS exhibit marked environmental recalcitrance, resulting in a persistent threat to both ecosystem integrity and public health[50]. Traditional advanced oxidation processes have limited efficiency in breaking the C–F bonds and achieving complete mineralization of PFAS. Therefore, advanced catalytic systems based on graphene have attracted extensive attention and have demonstrated a common C–F bond breaking mechanism in various advanced oxidation processes. In electrochemical oxidation systems, the graphene-based anode initiates the decarboxylation or desulfonation of PFAS through direct electron transfer, generating perfluoroalkyl radicals that subsequently undergo a continuous 'CF$_2$ unit sequential removal-defluorination' process, ultimately mineralizing into F$^-$, CO_2, and SO_4^{2-}[51]. In photocatalytic systems, the hydroxyl radicals (•OH) photogenerated on the surface of TiO_2-rGO composites attack the carbon site adjacent to the carboxyl group of perfluorooctanoic acid (PFOA), triggering decarboxylation and generating perfluoroalkyl radicals, which then undergo a 'hydration-elimination-hydrolysis' cycle to sequentially remove CF$_2$ units and release F$^-$,

Table 1 Separation performance of various graphene-based membranes

Membrane type	Contaminant	Concentration (mg L^{-1})	Rejection (%)	Water permeance (L m^{-2} h^{-1} bar^{-1})
GO-βCD membrane[31]	PFAS	0.1	90.0	22
NaOH-rGO membrane[32]	MPs	10	99.9	484.2
LGO membrane[33]	MPs	1	99.9	3,396
GO/ZrT-1-NH$_2$ membrane[34]	Antibiotics	100	99.0	10
G$_{10(1)}$/P$_{1.5}$-F$_{100\mu L}$ membrane[35]	Pendimethalin	10	99.9	20.7
GO-M-PhA-30 membrane[36]	Pendimethalin	50	99.4	19.0
rGO membrane[37]	Co^{2+}	22.7	99.9	72.4
CE7@ membrane[38]	Cs$^+$	20	94.4	15.8
G/D/Z/P membrane[39]	Cs$^+$	0.2	21.8	15,371

ultimately achieving complete mineralization of PFOA into CO_2 and H_2O[52]. Although electrochemical oxidation initiates PFAS degradation via direct electron transfer and photocatalytic systems through •OH radical attack, both processes share a common reaction pathway: 'decarboxylation or desulfonation to form perfluoroalkyl radicals, followed by sequential elimination of CF_2 groups and progressive C–F bond cleavage', ultimately leading to complete mineralization of the perfluorocarbon chain.

Similarly, for the catalytic degradation of polymer-based pollutants like MPs, the core lies in achieving oxidative cleavage of the polymer backbone. This process is initiated by photoexcitation-induced charge separation and migration, driving the continuous generation of reactive oxygen species. When graphene and semiconductors form heterojunctions, graphene, as an efficient electron-conducting medium, can significantly suppress the recombination of photogenerated carriers, thereby enhancing the yield and reactivity of reactive oxygen species. These highly oxidative species attack the C–H and C–C bonds on the surface of MPs, triggering chain oxidative cleavage, which is manifested as an increase in the carbonyl index, surface erosion, and the expansion of microscopic cracks, ultimately leading to the fragmentation and mineralization of the polymer. Research indicates that the graphene/TiO_2 heterojunction can effectively accelerate this cleavage process by enhancing the efficiency of charge separation[53]. It should be noted that if graphene is not integrated in the form of a heterojunction but co-exists with MPs as a dispersed phase, it may inhibit the photocatalytic reaction due to physical shielding and chemical quenching effects[54]. Therefore, the structural configuration of graphene and its interface interactions with pollutants and catalysts are key to regulating its catalytic degradation performance.

To effectively achieve the above reaction pathway, a variety of graphene-based catalytic degradation systems have been designed and optimized. In electrochemical cooperative technologies, reduced graphene oxide aerogel (rGA) modified by Fe_3O_4 or Cu nanoparticles was used as the cathode, coupled with boron-doped diamond (BDD) anode to construct an efficient heterogeneous Fenton-like system[55]. XPS and XRD analyses confirmed that the metal nanoparticles were stably loaded onto the three-dimensional rGA framework through chemical bonding, forming numerous catalytically active sites. Under the action of current, the rGA cathode can effectively activate H_2O_2 to generate a large amount of •OH radicals, while the BDD anode directly oxidizes the pollutants. The combined effect of both achieves the efficient degradation and fluorine removal of PFOA. UPLC-MS/MS analysis of the intermediate products revealed the degradation pathway of PFOA through sequential defluorination, providing direct evidence for the mineralization process. Electrochemical impedance spectroscopy indicated that the loading of metal nanoparticles significantly enhanced the electron conductivity of the cathode, thereby improving the catalytic efficiency; the SEM images after the cyclic experiments proved the good stability of the catalyst structure.

Additionally, the atomically engineered NiCo/GO aerogel functioned as an efficient cathode for in-situ H_2O_2 generation[56], achieving the degradation of ibuprofen (IBU) in water (2 mg L^{-1}) at an energy consumption of approximately 0.660 kW h m^{-3}. Theoretical calculations indicated that the Co sites preferentially adsorb O_2 molecules to promote H_2O_2 generation, whereas the Ni sites serve as active centers for H_2O_2 dissociation and activation (Fig. 3). The catalytic activity in single-atom systems is governed by the electronic interaction between the graphene support and the metal center. X-ray absorption spectroscopy confirms that MN_4 structures anchor Ni, Co, or Fe atoms at graphene double vacancies, forming
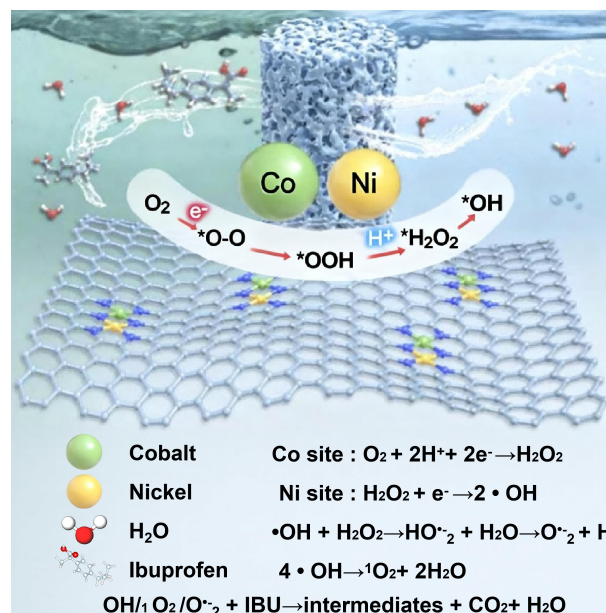

Fig. 3 Mechanism of the electro-Fenton process for the treatment of emerging contaminants[56].

atomically dispersed active sites. Coordination-induced charge transfer and orbital coupling modulate the metal d-band center, which influences intermediate adsorption and yields the oxygen evolution activity trend: Ni > Co > Fe. This demonstrates an atomic-level electronic structure-function relationship. Through spectroscopy and theoretical calculations, charge distribution between carbon and the metal site and its effect on the d-band center are quantified, clarifying how adsorption energies and reaction barriers in oxygen electrocatalysis are optimized. Thus, the high efficiency of the NiCo/GO system arises from graphene's precise electronic tuning of the metal center, enabling concerted thermodynamic and kinetic optimization of the catalytic cycle beyond a single active site.

Interestingly, integrating cobalt-doped g-C_3N_4 nanosheets into a membrane yields a nanoconfined environment that combines catalytic and separation functions[57]. The system demonstrates exceptional performance due to confinement-enhanced mass transfer and an optimized reaction pathway, leading to the rapid degradation of pollutants. In the field of photocatalysis, the MoS_2/rGO composite exhibits outstanding perfluorooctanoic acid (PFOA) degradation performance under indoor fluorescent light irradiation. In this system, rGO serves as an efficient electron-transfer medium, significantly enhancing the separation of photogenerated electron-hole pairs in MoS_2 while suppressing their recombination[58]. This synergistic interaction increases the yield of reactive oxygen species, leading to efficient decomposition and mineralization of PFOA. In addition, recent advances in the degradation of NCs using graphene-based materials have been systematically summarized, as presented in Table 2.

The research on graphene-based catalytic systems for the degradation of NCs has made significant progress, but their practical application still faces challenges. Key challenges in catalyst preparation, such as high synthesis costs, poor stability of nanomaterials, and potential environmental risks, currently hinder the practical deployment of graphene-based catalysts. Future efforts should prioritize the development of low-cost, scalable fabrication routes to enable economically viable production. Simultaneously, a deeper investigation into the long-term operational stability of these

Table 2 Catalytic performance of various graphene-based catalysts

Graphene-based catalyst	Contaminant	Concentration (mg L^{-1})	Degradation efficiency (%)
CMCD-TiO$_2$@Fe$_3$O$_4$@rGO[59]	Tetracycline	20	83.3
MnFe$_2$O$_4$@Bi$_2$WO$_6$-GO[60]	Tetracycline	10	99.3
rGO-TiO$_2$[61]	Diclofenac	10	85.5
rGO-CNCF[62]	Sulfamethazine	10	99.9
Ti/TiO$_2$-rGO[63]	PFOA	50	70
AgBr/GO/Bi$_2$WO$_6$[64]	Tetracycline	/	84
GO/SCN[65]	Bisphenol A	20	89.5
Pt/TiO$_2$@NRGO[66]	Tetracycline	27	81
Fe/g-C hybrid[67]	PFOA	1	> 85

nanocatalysts in complex, real-world matrices is essential. Furthermore, a comprehensive and proactive assessment of their potential environmental fate and long-term ecological impacts must be integrated into the design process. Addressing these fundamental issues—cost, stability, and safety—will be critical to unlocking the full application potential of graphene-based catalysis in environmental remediation.

Perspectives on the treatment of NCs via graphene-based material platforms

In conclusion, graphene-based materials represent a transformative platform with unparalleled potential to address the complex challenge of NCs. Their tunable surface chemistry, high capacity, and multifunctional capabilities position them not merely as incremental improvements but as foundational elements for next-generation remediation technologies. Moreover, the remediation of NCs in aquatic environments using graphene-based materials necessitates the integration of multidisciplinary expertise, including materials science, environmental engineering, chemistry, and toxicology, to establish a systematic research framework. This integrated approach is essential for effectively addressing current challenges posed by NCs and for building robust technical foundations to mitigate future environmental risks. Several meaningful outreach priorities about graphene-based materials are outlined below:

(1) Rational design of short-range mass-transfer nanochannels in graphene-based membranes. Future efforts should prioritize the construction of well-defined, stable nanochannels to fundamentally overcome the permeability-selectivity trade-off. This requires precise control over interlayer spacing, pore functionality, and structural durability under operational conditions, thereby significantly enhancing the efficiency and sustainability of NCs removal.

(2) Preconcentration and detection integration using graphene-based molecular sieves. Exploiting the precise molecular/ionic sieving properties of graphene-based membranes to enrich trace-level NCs and radioactive nuclides presents a promising avenue for enabling rapid, sensitive environmental monitoring. Research should focus on coupling selective capture with *in situ* detection platforms to develop continuous sensing systems.

(3) Development of graphene-based single-atom catalytic membranes. Integrating selective separation with catalytic degradation via single-atom catalysts embedded in graphene membranes represents a critical step toward energy-efficient, coupled remediation processes. Future studies should aim at designing stable, active, and selective catalytic interfaces that allow simultaneous separation and degradation of NCs in a single unit operation.

Declarations

Competing interests

The authors declare that they have no conflict of interest.

Author details

¹Shanghai Key Laboratory of Atomic Control and Application of Inorganic 2D Supermaterials, State key Laboratory of Materials for Advanced Nuclear Energy, Shanghai Applied Radiation Institute, Shanghai University, Shanghai 200444, China; ²China National Nuclear Corporation (CNNC) No.7 Research & Design Institute Co., Ltd, Taiyuan 030032, Shanxi Provincial Key Laboratory for Isotope Production and Irradiation Technology, Taiyuan, Shanxi 030012, China

References

[1] Zhao X, Wang X, He J, Feng C, Jin X, et al. 2025. Time to strengthen the governance of new contaminants in the environment. *Nature Communications* 16:7775

[2] Zhang X, Li L, Xie Z, Ma J, Li YF, et al. 2024. Exploring global oceanic persistence and ecological effects of legacy persistent organic pollutants across five decades. *Science Advances* 10:5534

[3] Gan J. 2025. Risk avoidance as a practical solution to safeguard against emerging contaminants. *Nature Water* 3(12):1334−1335

[4] Cui HL, Gao SH, Wang HC, Zhang LY, Luo Y, et al. 2025. Big data integration for environmental risk assessment of emerging contaminants. *Nature Sustainability*

[5] Evich MG, Davis MJB, McCord JP, Acrey B, Awkerman JA, et al. 2022. Per- and polyfluoroalkyl substances in the environment. *Science* 375:eabg9065

[6] Yang L, Chen Z, Goult CA, Schlatzer T, Paton RS, et al. 2025. Phosphate-enabled mechanochemical PFAS destruction for fluoride reuse. *Nature* 640:100−106

[7] Zhang H, Chen JX, Qu JP, Kang YB. 2024. Photocatalytic low-temperature defluorination of PFASs. *Nature* 635:610−617

[8] Thompson RC, Courtene-Jones W, Boucher J, Pahl S, Raubenheimer K, et al. 2024. Twenty years of microplastic pollution research—what have we learned? *Science* 386:eadl2746

[9] Rathi BS, Kumar PS, Show PL. 2021. A review on effective removal of emerging contaminants from aquatic systems: current trends and scope for further research. *Journal of Hazardous Materials* 409:124413

[10] Ateia M, Wei H, Andreescu S. 2024. Sensors for emerging water contaminants: overcoming roadblocks to innovation. *Environmental Science & Technology* 58:2636−2651

[11] Carter L, Davis C. 2025. Emerging contaminants in agricultural systems. *Nature Reviews Earth & Environment* 6:320

[12] Taibl KR, Dunlop AL, Barr DB, Li YY, Eick SM, et al. 2023. Newborn metabolomic signatures of maternal per- and polyfluoroalkyl substance exposure and reduced length of gestation. *Nature Communications* 14:3120

[13] Guan Y, Liu Z, Yang N, Yang S, Quispe-Cardenas LE, et al. 2024. Near-complete destruction of PFAS in aqueous film-forming foam by integrated photo-electrochemical processes. *Nature Water* 2:443−452

[14] Ames JL, Sharma V, Lyall K. 2025. Effects of early-life PFAS exposure on child neurodevelopment: a review of the evidence and research gaps. *Current Environmental Health Reports* 12:9

[15] Huang H, Hou J, Li M, Wei F, Liao Y, et al. 2025. Microplastics in the bloodstream can induce cerebral thrombosis by causing cell obstruction and lead to neurobehavioral abnormalities. *Science Advances* 11:eadr8243

[16] Wang Y, Xiang L, Amelung W, Elsner M, Gan J, et al. 2023. Micro- and nanoplastics in soil ecosystems: analytical methods, fate, and effects. *TrAC Trends in Analytical Chemistry* 169:117309

[17] Wang F, Xiang L, Sze-Yin Leung K, Elsner M, Zhang Y, et al. 2024. Emerging contaminants: a one health perspective. *The Innovation* 5(4):100612

[18] Yasunari TJ, Stohl A, Hayano RS, Burkhart JF, Eckhardt S, et al. 2011. Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident. *Proceedings of the National Academy of Sciences of the United States of America* 108:19530−19534

[19] Liu G, Jin W, Xu N. 2015. Graphene-based membranes. *Chemical Society Reviews* 44:5016−5030

[20] Chen L, Shi G, Shen J, Peng B, Zhang B, et al. 2017. Ion sieving in graphene oxide membranes via cationic control of interlayer spacing. *Nature* 550:415−418

[21] Chen J, Liu X, Ding Z, He Z, Jiang H, et al. 2023. Multistage filtration desalination via ion self-rejection effect in cation-controlled graphene oxide membrane under 1 bar operating pressure. *Nano Letters* 23:10884−10891

[22] Chen J, Li J, Liu X, He Z, Shi G. 2023. An anomalous anion transfer order in graphene oxide membranes induced by anion-π interactions. *Physical Chemistry Chemical Physics* 25:13260−13264

[23] Joshi RK, Carbone P, Wang FC, Kravets VG, Su Y, et al. 2014. Precise and ultrafast molecular sieving through graphene oxide membranes. *Science* 343:752−754

[24] Bunch JS, Verbridge SS, Alden JS, van der Zande AM, Parpia JM, et al. 2008. Impermeable atomic membranes from graphene sheets. *Nano Letters* 8:2458−2462

[25] Zhao S, Zhu H, Wang H, Rassu P, Wang Z, et al. 2019. Free-standing graphene oxide membrane with tunable channels for efficient water pollution control. *Journal of Hazardous Materials* 366:659−668

[26] Liu J, Wang S, Yang R, Li L, Liang S, et al. 2022. Bio-inspired graphene oxide-amino acid cross-linked framework membrane trigger high water permeance and high metal ions rejection. *Journal of Membrane Science* 659:120745

[27] Dai F, Zhou F, Chen J, Liang S, Chen L, et al. 2021. Ultrahigh water permeation with a high multivalent metal ion rejection rate through graphene oxide membranes. *Journal of Materials Chemistry A* 9:10672−10677

[28] Yi R, Xia X, Yang R, Yu R, Dai F, et al. 2021. Selective reduction of epoxy groups in graphene oxide membrane for ultrahigh water permeation. *Carbon* 172:228−235

[29] Dai F, Gu Z, Hu S, Peng B, Yang R, et al. 2024. Unexpected self-assembly of nanographene oxide membranes upon electron beam irradiation for ultrafast ion sieving. *Advanced Science* 11:2404001

[30] Yan L, Chen J, Zhang Z, Liu Z, Ding T, et al. 2025. Reduced graphene oxide membrane with small nanosheets for efficient and ultrafast removal of both microplastics and small molecules. *Journal of Hazardous Materials* 487:137078

[31] Mahofa E, El Meragawi S, Vilayatteri MA, Dwivedi S, Panda MR, et al. 2025. Manipulating intrapore energy barriers in graphene oxide nanochannels for targeted removal of short-chain PFAS. *ACS Nano* 19:14724−14755

[32] Jian L, Qiu Y, Zhang Z, Feng A, Shi G, et al. 2025. Reduced graphene oxide membrane with wrinkled surfaces for ultrafast and stable microplastics removal. *Journal of Environmental Chemical Engineering* 13:120454

[33] Sun J, Xiong Y, Jia H, Han L, Yin K. 2024. Superb microplastics separation performance of graphene oxide tuned by laser bombardment. *Journal of Hazardous Materials* 461:132599

[34] Kuang B, Xiang X, Su P, Yang W, Li W. 2022. Self-assembly of stable and high-performance molecular cage-crosslinked graphene oxide membranes for contaminant removal. *Journal of Hazardous Materials* 439:129708

[35] Abebe SH, Subrahmanya TM, Austria HFM, Nayak S, Huang TH, et al. 2024. High performance lamellar structured graphene oxide nanocomposite membranes via Fe_3O_4-coordinated phytic acid control of interlayer spacing for organic solvent nanofiltration (OSN). *Chemical Engineering Journal* 495:153451

[36] Abebe SH, Mulawarman RI, Cayron RH, Nayak S, Subrahmanya TM, et al. 2025. Zwitterionic M-PhA modified GO nanocomposite membranes for enhanced organic solvent nanofiltration and wastewater treatment with antifouling performance. *Journal of Membrane Science* 736:124596

[37] Zhou F, Xia X, Wei Y, Sun H, Yao H, et al. 2024. Rapid and efficient separation of radioactive cesium ion/other radioactive ions by reduced graphene oxide membrane. *Journal of Environmental Chemical Engineering* 12:114284

[38] Huang Y, Chen J, Liu H, Wang Y, Lu M, et al. 2024. Crown ether intercalated graphene oxide membranes for highly efficient sieving of cesium with a large water permeability. *Separation and Purification Technology* 339:126702

[39] Zhang G, Fu R, Li Y, Wang X, Niu Z, et al. 2025. Super-large flux submicron porous membrane for removal of metal ions from low-level radioactive wastewater. *Chemical Engineering Journal* 504:159154

[40] Lozada-Hidalgo M, Hu S, Marshall O, Mishchenko A, Grigorenko A, et al. 2016. Sieving hydrogen isotopes through two-dimensional crystals. *Science* 351:68−70

[41] Lozada-Hidalgo M, Zhang S, Hu S, Esfandiar A, Grigorieva IV, et al. 2017. Scalable and efficient separation of hydrogen isotopes using graphene-based electrochemical pumping. *Nature Communications* 8:15215

[42] Mohammadi A, Daymond MR, Docoslis A. 2020. Graphene oxide membranes for isotopic water mixture filtration: preparation, physicochemical characterization, and performance assessment. *ACS Applied Materials & Interfaces* 12:34736−34745

[43] Su P, Zhou M, Lu X, Yang W, Ren G, et al. 2019. Electrochemical catalytic mechanism of N-doped graphene for enhanced H_2O_2 yield and in-situ degradation of organic pollutant. *Applied Catalysis B: Environmental* 245:583−595

[44] Wan Z, Wang J. 2017. Degradation of sulfamethazine using Fe_3O_4-Mn_3O_4/reduced graphene oxide hybrid as Fenton-like catalyst. *Journal of Hazardous Materials* 324:653−664

[45] Jiang WL, Xia X, Han JL, Ding YC, Haider MR, et al. 2018. Graphene modified electro-Fenton catalytic membrane for *in situ* degradation of antibiotic florfenicol. *Environmental Science & Technology* 52:99772−99982

[46] Zhang Z, He Z, Li K, Liu J, Liu X, et al. 2025. Organic molecules induce the formation of hopper-like NaCl crystals under rapid evaporation as microcatalytic reactors to facilitate micro/nanoplastic degradation. *Nano Letters* 25:2334–2341

[47] Yue D, Zeng T, Li Y, Lin J, Xiao J, et al. 2025. T-shaped Fe-based multi-stoichiometry stereoscopic composite catalyst with ultrahigh activity toward Fenton-like water treatment, synthesized via graphene-controlled growth. *Physical Review Letters* 135:038001

[48] Zhu M, Lin J, Yuan M, Li Y, Cheng N, et al. 2025. Atomically dispersed FeO_x species functionalized Fe_2O_3 nano-island clusters toward efficient Fenton-like catalysis. *Advanced Functional Materials* 36(5):e14460

[49] Nisar A, Saeed M, Muneer M, Usman M, Khan I. 2022. Synthesis and characterization of ZnO decorated reduced graphene oxide (ZnO-rGO) and evaluation of its photocatalytic activity toward photodegradation of methylene blue. *Environmental Science and Pollution Research* 29:418–430

[50] Liu X, Sau A, Green AR, Popescu MV, Pompetti NF, et al. 2025. Photocatalytic C–F bond activation in small molecules and polyfluoroalkyl substances. *Nature* 637:601–607

[51] Duinslaeger N, Radjenovic J. 2022. Electrochemical degradation of per- and polyfluoroalkyl substances (PFAS) using low-cost graphene sponge electrodes. *Water Research* 213:118148

[52] Gomez-Ruiz B, Ribao P, Diban N, Rivero MJ, Ortiz I, et al. 2018. Photocatalytic degradation and mineralization of perfluorooctanoic acid (PFOA) using a composite TiO_2-rGO catalyst. *Journal of Hazardous Materials* 344:950–957

[53] Ibrahim N, Rahman AMNAA, Shafiq MD, Lockman Z, Jaafar M, et al. 2025. Microplastic pollution: sources, degradation mechanisms, analytical advances, and mitigation strategies for environmental sustainability. *Reviews of Environmental Contamination and Toxicology* 263:27

[54] Gong Z, Wang J, Wu X, Shao S, Fan B, et al. 2023. Interactions between graphene oxide and polyester microplastics changed their phototransformation process and potential environmental risks: mechanism insights. *Separation and Purification Technology* 307:122769

[55] Li Y, Che N, Liu N, Li C. 2023. Degradation of perfluorooctanoic acid (PFOA) using multiphase Fenton-like technology by reduced graphene oxide aerogel (rGAs) combined with BDD electrooxidation. *Chemical Engineering Journal* 478:147443

[56] Dong C, Chen Y, Yang C, Li P, Zhang Y, et al. 2024. Pinning-effect single-atom NiCo alloy embedded graphene-aerogel in electro-Fenton process for rapid degradation of emerging contaminants. *Applied Catalysis B: Environment and Energy* 357:124286

[57] Zhang W, Zhang S, Meng C, Zhang Z. 2023. Nanoconfined catalytic membranes assembled by cobalt-functionalized graphitic carbon nitride nanosheets for rapid degradation of pollutants. *Applied Catalysis B - Environment and Energy* 322:122098

[58] Norsham INM, Sambasevam KP, Shahabuddin S, Jawad AH, Baharin SNA. 2022. Photocatalytic degradation of perfluorooctanoic acid (PFOA) via MoS_2/rGO for water purification using indoor fluorescent irradiation. *Journal of Environmental Chemical Engineering* 10:108466

[59] Duinslaeger N, Doni A, Radjenovic J. 2023. Impact of supporting electrolyte on electrochemical performance of borophene-functionalized graphene sponge anode and degradation of per- and polyfluoroalkyl substances (PFAS). *Water Research* 242:120232

[60] Zamani A, Tadjarodi A. 2024. Development and fabrication of graphene oxide and reduced graphene oxide incorporated $MnFe_2O_4$@Bi_2WO_6 nanocomposite for efficient degradation of antibiotic drug as water contaminant under visible-light illumination. *Ceramics International* 50:53456–53481

[61] Alkharabsheh S, McMichael S, Singhal A, Rioja-Cabanillas A, Zamora P, et al. 2024. Bench-scale photoelectrocatalytic reactor utilizing rGO-TiO_2 photoanodes for the degradation of contaminants of emerging concern in water. *Process Safety and Environmental Protection* 182:833–844

[62] Zhou J, Sun Q, Wang X, Liu Y, Xia S, et al. 2024. High performance of reduced graphene oxide and g-C_3N_4 Co-doped $CuFe_2O_4$ for peroxymonosulfate activation under visible light: degradation process of sulfamethazine via a singlet oxygen dominated pathway. *Chemical Engineering Journal* 485:149571

[63] Kasalica K, Stojadinović S, Lješević M, Ivanov P, Yamamoto A, et al. 2025. Photocatalytic degradation of PFOA over rGO-doped TiO_2 coatings formed by plasma electrolytic oxidation. *Journal of Environmental Chemical Engineering* 13:117452

[64] Budiarso IJ, Dabur VA, Rachmantyo R, Judawisastra H, Hu C, et al. 2024. Carbon nitride- and graphene-based materials for the photocatalytic degradation of emerging water pollutants. *Materials Advances* 5:2668–2688

[65] Sura A, Nain S. 2024. Visible light driven degradation of BPA and LDPE microplastic films using GO/SCN nanocomposite. *RSC Advances* 14:35336–35347

[66] Moharrami E, Keshipour S. 2025. Photocatalytic degradation of tetracycline antibiotic using nitrogen-doped reduced graphene oxide-supported titania/platinum nanoparticles. *npj Materials Degradation* 9:57

[67] Moreira R, B. Esfahani E, A. Zeidabadi F, Rostami P, Thuo M, et al. 2024. Hybrid graphenic and iron oxide photocatalysts for the decomposition of synthetic chemicals. *Communications Engineering* 3:114