Chapter-5

Reduce Graphene oxide applications in wastewater treatment and oil spillage

5.1. Introduction

5.1.1 Reduced Graphene Oxide (rGO) for Environmental Applications

Environmental pollution has become one of the most pressing global challenges of the 21st century, with water contamination standing out as a critical concern due to its direct implications for both ecological integrity and human well-being [1]. Among various forms of water pollution, oil spills and the discharge of untreated or partially treated industrial wastewater are particularly hazardous. These pollutants not only disrupt aquatic ecosystems by altering the oxygen balance and damaging marine biodiversity, but also pose significant health risks to humans through the contamination of drinking water sources and the food chain [2], [3].

Traditional remediation strategies, such as the use of chemical dispersants, skimmers, booms, and other physical containment systems, have been widely employed in response to oil spill incidents and wastewater treatment. However, these conventional approaches often suffer from several critical limitations, including low removal efficiency, generation of secondary pollutants, high operational and maintenance costs, and limited applicability in harsh environmental conditions [4], [5]. As a result, the scientific community has increasingly turned its focus toward the development of innovative, efficient, and environmentally sustainable materials capable of addressing these complex challenges.

In recent years, nanomaterials have gained substantial attention in this regard due to their high surface area, tunable surface chemistry, and potential for functionalization. Among them, graphene and its derivatives have emerged as particularly promising candidates for water purification and oil spill remediation applications [6]. Specifically, reduced graphene oxide (rGO) stands out for its exceptional physicochemical properties, including high mechanical strength, hydrophobicity, electrical conductivity, and the presence of abundant active sites that facilitate adsorption and separation processes [7]. These properties make rGO-based materials highly attractive for applications such as oil-water separation, adsorption of heavy metals, and removal of organic pollutants from contaminated water sources [8]. Furthermore, the potential for low-cost synthesis and environmental compatibility positions rGO as a sustainable alternative to conventional materials, aligning with the goals of green chemistry and circular economy principles [9].

5.1.2 Graphene and Graphene Oxide: From Discovery to Application

Graphene, a single atomic layer of sp^2-hybridized carbon atoms arranged in a two-dimensional hexagonal (honeycomb) lattice, is widely regarded as one of the most promising nanomaterials of the 21st century. Its unique structure imparts a combination of exceptional physicochemical properties, including a high specific surface area (~2630 m^2/g), outstanding mechanical strength (~130 GPa tensile strength), and ultrahigh thermal and electrical conductivity, which have led to significant interest in applications across electronics, energy storage, composites, and environmental remediation [10, 11].

However, pristine graphene is intrinsically hydrophobic, limiting its compatibility with water and polar solvents. This hydrophobic nature, along with strong π–π interactions between sheets, causes graphene to aggregate in aqueous media, thereby reducing its surface area and reactivity—factors which are critical in applications such as water purification, sensing, and oil–water separation [12]. To mitigate these challenges, graphene is commonly synthesized via the chemical oxidation of graphite to produce graphene oxide (GO), a process that introduces various oxygen-containing functional groups—such as hydroxyl (–OH), epoxy (–O–), and carboxyl (–COOH)—onto the graphene structure [13,14].

These functional groups impart GO with a strong hydrophilic character, allowing it to readily disperse in water and form stable colloidal suspensions. In addition to enhancing water compatibility, these groups increase the chemical reactivity of GO, enabling further functionalization for specific applications. This makes GO not only easier to process in aqueous systems, but also a versatile platform for developing materials suited to environmental remediation, including membrane fabrication, dye removal, and oil–water separation [15-17]. Furthermore, the hydrophilic nature and negative surface charge of GO in water enable strong interactions with metal ions, organic pollutants, and oils, facilitating selective adsorption and separation processes [18].

5.1.3 The Role of Reduced Graphene Oxide (rGO)

While graphene oxide (GO) possesses excellent dispersibility in water due to its abundant oxygen-containing functional groups, this high level of oxidation significantly disrupts the extended sp^2 carbon conjugation network. As a result, GO exhibits diminished electrical conductivity and reduced mechanical integrity compared to pristine graphene [16,19]. This degradation of electronic and structural properties arises from the introduction of hydroxyl, epoxy, and carboxyl groups that convert sp^2-hybridized carbon atoms into sp^3-hybridized configurations, thereby impeding charge delocalization and reducing π–π stacking interactions.

To recover the electrical and mechanical performance of graphene, GO is typically subjected to a reduction process, which removes a portion of these oxygen-containing groups and partially restores the aromatic carbon framework. The product, known as reduced graphene oxide (rGO), exhibits enhanced conductivity, improved thermal stability, and increased hydrophobicity relative to GO [16,12]. However, achieving an optimal balance during the reduction process is crucial. Excessive reduction may eliminate surface functional groups required for adsorption or chemical anchoring, while insufficient reduction may leave too many defects, limiting electrical performance and structural order [20].

Various reduction techniques have been developed to tailor the properties of rGO. Thermal reduction, involving high-temperature treatment (typically 200–1000 °C) under inert or reducing atmospheres, offers a relatively simple route to significantly decrease oxygen content and increase graphitization. However, the high temperatures can cause sheet restacking or damage to the graphene structure [15,21]. Alternatively, microwave-assisted reduction provides rapid, localized heating, facilitating the quick removal of oxygen groups while potentially preserving porosity and minimizing aggregation [22,23]. These methods offer varying degrees of reduction and structural restoration, and the final physicochemical properties of rGO—including surface area, pore structure, and surface chemistry—are highly dependent on the reduction parameters and chosen method.

Understanding and controlling the reduction process is therefore essential for tailoring rGO-based materials for specific applications, such as oil–water separation, pollutant adsorption, and energy storage, where a combination of electrical conductivity, porosity, and surface reactivity is often required.

5.1.4 Advancing Environmental Remediation with rGO

This study is cantered on the synthesis and in-depth characterization of reduced graphene oxide (rGO), with a particular focus on comparing two prevalent reduction techniques: the conventional thermal reduction method and the emerging microwave-assisted approach. Thermal reduction, a widely used method, involves subjecting graphene oxide (GO) to elevated temperatures under inert atmospheres, facilitating the removal of oxygen functional groups and partial restoration of the graphitic structure [21]. However, microwave-assisted reduction has recently gained attention due to its rapid heating rates, energy efficiency, and potential to preserve desirable morphological features such as porosity and surface defects critical for adsorption applications [22,23].

Our aim is to demonstrate that microwave-assisted reduction can yield rGO with superior structural, chemical, and morphological properties compared to thermally reduced counterparts, thereby enhancing its functionality for environmental remediation. The resultant rGO exhibits a large specific surface area and a unique pore architecture that promotes selective oil adsorption, making it a promising candidate for oil spill clean-up efforts [24]. Moreover, the partial retention of surface functional groups alongside restored hydrophobicity allows rGO to effectively interact with a wide range of aqueous contaminants, including organic dyes, heavy metals, and other toxic substances commonly found in industrial wastewater [25,26].

Throughout this research, comprehensive analyses including spectroscopic, microscopic, and adsorption studies are employed to investigate the material's evolution at each synthesis stage. By correlating the structural and chemical transformations with performance metrics, we aim to establish a fundamental understanding of how reduction methods influence rGO's adsorptive capabilities. This knowledge not only contributes to optimizing rGO synthesis for environmental applications but also provides insights for the broader development of sustainable, high-performance nanomaterials for pollution mitigation.

5.1.5 Reduced Graphene Oxide (rGO) in Environmental Applications: Focus on Water Treatment

Reduced graphene oxide (rGO) is a highly versatile material for environmental remediation, attributed to its unique combination of physicochemical properties, including a high specific surface area, tunable pore structure, chemical stability, and partial restoration of graphitic domains. These properties make rGO an attractive candidate for diverse applications such as water treatment, oil spill cleanup, and air purification [25,26]. This section focuses on the pivotal role of rGO in water treatment, highlighting its multifunctional capabilities.

5.1.5.1 Water Treatment

The effectiveness of rGO in water purification arises from its ability to adsorb a wide spectrum of pollutants through a combination of physical adsorption mechanisms and chemical interactions with residual surface functional groups [27,28]. The material's large surface area and mesoporous structure facilitate rapid diffusion and high capacity, while its chemical heterogeneity allows for specific pollutant binding.

5.1.5.2 Removal of Dyes and Organic Pollutants:

Organic dyes such as Methylene Blue, Rhodamine B, and Congo Red pose severe environmental and health risks due to their toxicity and persistence. rGO adsorbs these dyes primarily through π–π stacking interactions between the conjugated sp^2 domains of the graphene sheets and the aromatic rings of the dye molecules [29,30]. The large surface area and interconnected mesopores in rGO enable efficient capture and rapid transport of bulky dye molecules, resulting in high adsorption capacities and fast kinetics.

5.1.5.3 Heavy Metal Ion Adsorption:

Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+}) are common water contaminants with significant toxicological concerns. The residual oxygen-containing functional groups—especially hydroxyl (–OH) and carboxyl (–COOH) moieties—on rGO serve as active sites for chelation and electrostatic binding with metal ions [31,32]. This enables effective removal of heavy metals via surface complexation mechanisms, even at low pollutant concentrations.

5.1.5.4 Antibacterial Properties:

Beyond adsorption, rGO exhibits inherent antibacterial activity, contributing to microbial disinfection in water treatment applications. The sharp edges of graphene sheets can physically disrupt bacterial cell membranes, leading to leakage of intracellular contents and cell death [33,34] Furthermore, rGO can induce the generation of reactive oxygen species (ROS), causing oxidative stress that damages bacterial proteins and DNA, thereby enhancing its bactericidal efficacy [35]. These properties position rGO as a dual-function material capable of removing chemical pollutants and reducing microbial load simultaneously.

5.1.6 Oil Spill Clean-up

Reduced graphene oxide (rGO) exhibits significant potential in oil spill remediation owing to its regained hydrophobicity and inherent oleophilic properties, which enable selective oil absorption while effectively repelling water. This unique combination facilitates highly efficient separation of oil-water mixtures, a critical requirement for environmental clean-up operations.

5.1.6.1 High Adsorption Capacity:

The hierarchical and porous architecture of rGO, especially when fabricated into three-dimensional structures such as foams or aerogels, results in an exceptionally high volume-to-surface-area ratio. These features allow rGO-based materials to adsorb vast amounts of oil, frequently exceeding 100 times their own weight [36,37]. The interconnected porous networks promote rapid oil uptake and retention, making rGO foams effective sorbents for diverse oil types, including crude oil, diesel, and lubricants.

5.1.6.2 Excellent Reusability:

One of the practical advantages of rGO foams and aerogels is their facile recovery after oil adsorption. The adsorbed oil can be efficiently removed by mechanical squeezing, centrifugation, or simple distillation processes, enabling multiple reuse cycles without a significant decline in adsorption efficiency [38,39]. This reusability not only reduces operational costs but also enhances sustainability in oil spill response strategies.

5.1.6.3 Selective Oil Adsorption:

The synergy between rGO's hydrophobic surface and low surface energy facilitates selective affinity towards oil droplets over water molecules [40]. This selective binding is driven by reduced interfacial tension between the oil and rGO surface, ensuring effective separation even in complex emulsified oil-water systems. Such selectivity is crucial for minimizing secondary contamination and maximizing the efficiency of oil recovery during environmental remediation efforts.

Collectively, these properties underscore the promise of rGO-based materials as next-generation sorbents for efficient, sustainable, and cost-effective oil spill clean-up operations.

5.1.7 Air Purification

Although the application of reduced graphene oxide (rGO) in air purification is less explored compared to water treatment and oil spill clean-up, emerging research highlights its potential as an effective adsorbent and catalyst support for gaseous pollutant removal. The material's large surface area, tuneable porosity, and functionalize surface make it a versatile candidate for addressing air quality challenges, particularly in indoor and industrial environments.

5.1.8 Volatile Organic Compounds (VOCs) Adsorption:

rGO's extensive surface area and interconnected porous structure enable it to efficiently adsorb a wide range of volatile organic compounds (VOCs), including hazardous gases such as benzene, formaldehyde, and toluene [41,42]. These compounds pose serious health risks due to their toxicity and volatility. The adsorption mechanism primarily involves physisorption complemented by chemical interactions, which can be further enhanced by surface functionalization with specific groups (e.g., amines or thiols) to improve selective affinity toward target VOC molecules [43].

5.1.9 Catalytic Activity:

Beyond adsorption, rGO functions as an excellent catalyst or catalyst support for decomposing toxic gaseous pollutants such as nitrogen oxides (NOx) and carbon monoxide (CO). Its high surface area provides an ideal platform for dispersing catalytic nanoparticles (e.g., metal oxides or noble metals), increasing the number of active sites and improving catalytic efficiency [44,45]. This catalytic role not only facilitates the conversion of harmful gases into benign products like nitrogen and carbon dioxide but also enhances the material's durability and recyclability in air purification devices.

Collectively, these attributes suggest that rGO-based materials could play a significant role in next-generation air filtration systems, offering multifunctional capabilities for trapping and degrading airborne pollutants.

5.2 Application for rGO-M in Environmental Beingness

5.2.1 Adsorption Efficiency of rGO-M in Wastewater Treatment

Adsorption experiments were systematically conducted to evaluate the effectiveness of microwave-reduced graphene oxide (rGO-M) in treating complex industrial wastewater, as illustrated in Figure 5.1. The initial characterization of the wastewater revealed several critical physicochemical parameters: a highly alkaline pH of 13.8, elevated conductivity at 12,950 µS/cm, significant turbidity of 187 NTU, and substantial concentrations of total hardness (170 ppm), calcium (66 ppm), magnesium (104 ppm), iron (0.3 ppm), chloride ions (250 ppm), and total organic carbon (TOC) at 22.74 ppm. These values underscored the challenging nature of the wastewater, necessitating an effective adsorption material for pollutant removal.

To quantitatively assess the adsorption capacities, heat-treated reduced graphene oxide (rGO) and microwave-reduced graphene oxide (rGO-M) were introduced into the wastewater at varying dosages of 0.5 g/L, 1.0 g/L, and 1.5 g/L. Batch adsorption experiments were meticulously performed under controlled conditions, with variables such as temperature and contact time optimized to maximize pollutant removal efficiency (Scholte et al., 1984). Samples were withdrawn at predetermined intervals to monitor the reduction in pollutant concentrations over time.

The experimental results conclusively demonstrated that rGO-M outperformed conventional heat-treated rGO at all dosages tested. Specifically, rGO-M exhibited superior removal efficiencies for total organic carbon (TOC), calcium hardness, magnesium hardness, and overall total hardness (Michelin et al., 2015). For example, at a dosage of 1.0 g/L, rGO-M achieved reductions of 80% and 85% in total hardness and calcium hardness, respectively, compared to 70% and 75% achieved by rGO. Moreover, rGO-M recorded a 60% reduction in TOC, surpassing the 55% reduction obtained by rGO.

Further highlighting the efficacy of rGO-M, its adsorption capacities were calculated at the 1.0 g/L dosage, yielding values of 136 mg/g for total hardness and 13.65 mg/g for TOC removal. At the highest dosage of 1.5 g/L, rGO-M demonstrated outstanding removal efficiencies, achieving 85% reduction in total hardness and 61% reduction in TOC. These enhanced performances can be attributed to the increased surface area and enriched functional groups introduced during microwave-assisted reduction, which provide more active sites for adsorption and stronger interactions with pollutants.

In summary, the results establish rGO-M as a highly promising material for wastewater treatment and environmental remediation, offering superior adsorption capabilities relative to traditional rGO. Its improved structural and chemical properties obtained through microwave treatment render it particularly effective for the removal of complex pollutants in industrial wastewater.

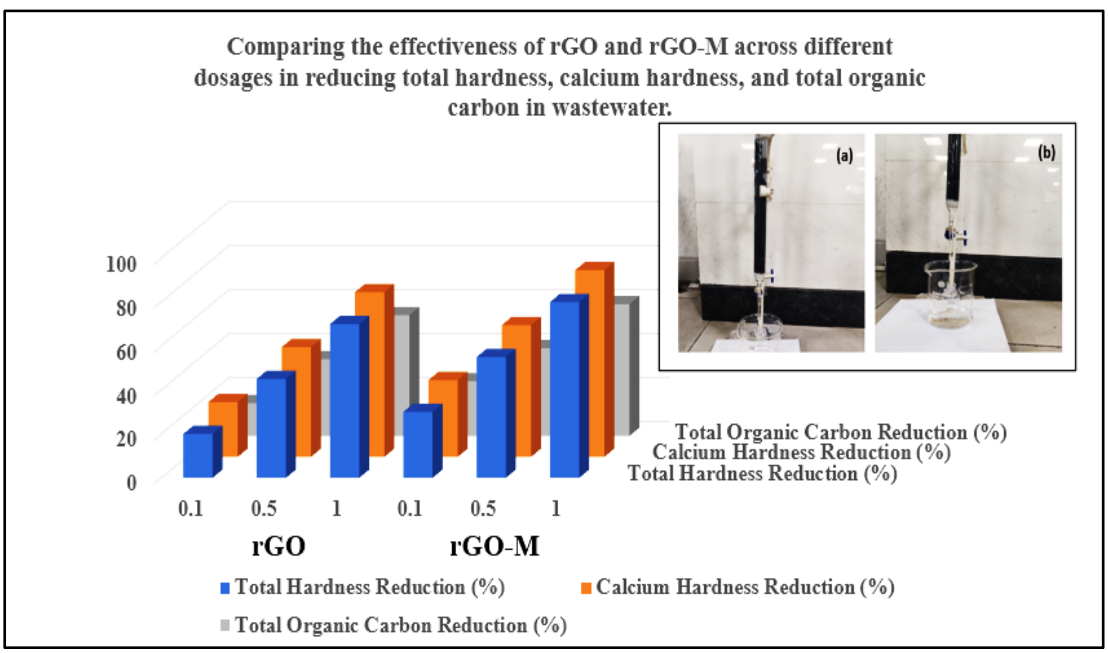

Figure 5.1: Adsorption efficiency of rGO-M

Figure 5.1 Comparing the effectiveness of rGO and rGO-M across different dosages in reducing total hardness, calcium hardness, and total organic carbon in wastewater. Insight showing Adsorption capacity of (a) rGO treated wastewater and (b) rGO-M treated wastewater Treated with rGO-M Showing Improved Water Quality.

5.2.2 Oil Spill Remediation Performance

Figure 5.2 illustrates the sequential stages of oil spill remediation using microwave-reduced graphene oxide (rGO-M) in the presence of toluene, highlighting both qualitative visual changes and quantitative adsorption data that collectively demonstrate the efficacy of rGO-M in oil removal.

In Figure 5.2(a), the initial scenario is presented, where oil is dispersed across the surface of the toluene, effectively simulating an oil spill with conspicuous patches of floating oil visible on the solvent's surface. This establishes the baseline condition prior to remediation.

Following the introduction of rGO-M into the system, Figure 5.9(b) captures the early phase of the adsorption process. Darkened regions begin to emerge on the toluene surface, corresponding to zones where rGO-M has actively adsorbed oil. Quantitatively, conventional reduced graphene oxide (rGO) adsorbed approximately 110 mg of oil per gram of material, corresponding to a 55% oil absorbance capacity within 30 minutes. In contrast, rGO-M exhibited a substantially higher oil adsorption capacity, calculated at 190 mg of oil per gram of rGO-M, translating to an 85% removal efficiency within the same time frame. This significant enhancement reflects the superior surface characteristics and pore architecture of rGO-M, which facilitate rapid and selective oil uptake.

By Figure 5.2(c), the majority of the oil has been absorbed by rGO-M, resulting in a noticeably clearer toluene surface. The figure depicts a scraping tool being used to collect the aggregated rGO-M-oil complex, underscoring the practical feasibility of removing the oil-saturated adsorbent from the solvent. This aggregation is facilitated by the hydrophobic and oleophilic nature of rGO-M, which promotes strong affinity and binding to oil molecules.

Finally, Figure 5.2(d) demonstrates the near-complete remediation of the toluene surface, where the visible oil is largely absent, and the water appears substantially clearer. The rGO-M has consolidated into a dark clump, representing the collected oil-loaded adsorbent ready for recovery and potential reuse (Verstraete et al., 2010). This progression of images and data clearly illustrates the remarkable effectiveness of rGO-M for adsorbing and removing oil from organic solvent environments, highlighting its considerable potential as a highly efficient material for oil spill remediation.

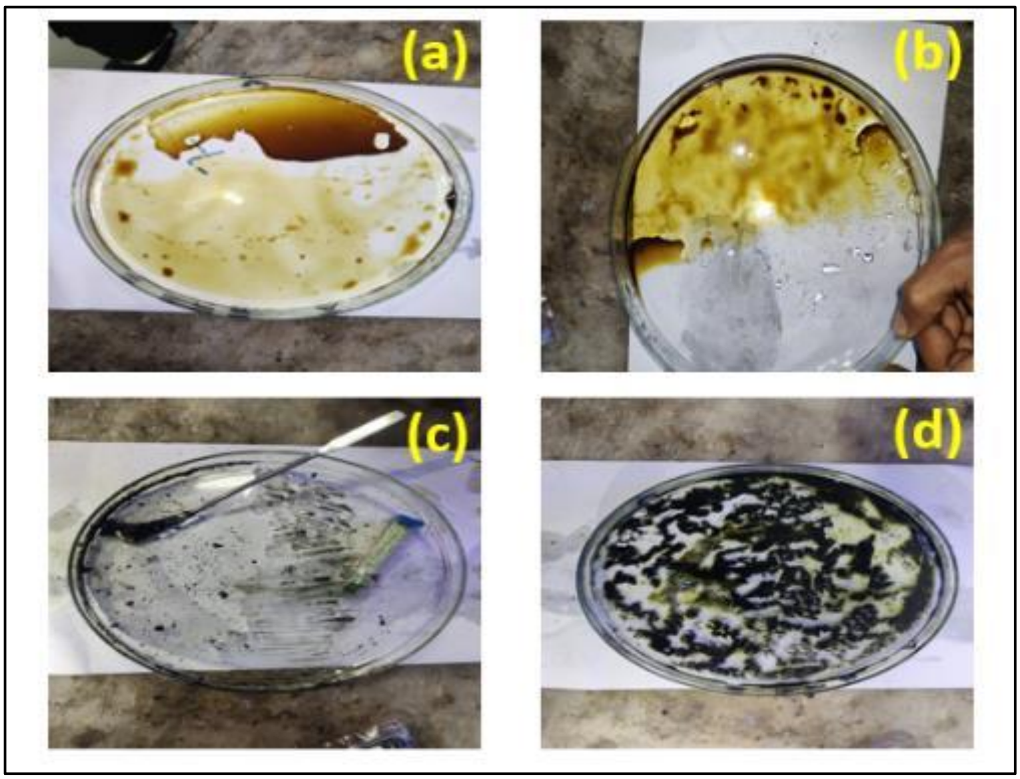

Figure 5.2: Stages of oil spill remediation using rGO-M in toluene. (a) Initial oil patches on the surface. (b) rGO-M adsorbs oil, reducing visible oil. (c) Surface clears as rGO-M absorbs more oil. (d) Toluene is nearly clear, with rGO-M forming a dark clump. Adsorption capacity: 190 mg oil/g, 85% removal in 30 minutes.

5.2.3 Adsorption Studies of rGO in Oil Spill Remediation

Figure 5.3(a) depicts the oil adsorption capacity of microwave-reduced graphene oxide (rGO-M), expressed in milligrams of oil adsorbed per gram of rGO-M, as a function of contact time. The adsorption capacity increases rapidly during the initial stages, reaching approximately 60 mg/g within the first minute, which underscores the fast adsorption kinetics of rGO-M. This rapid initial uptake is indicative of abundant active sites and favourable interactions between the hydrophobic rGO-M surface and the oil molecules. Adsorption capacity continues to increase more gradually after the initial phase, peaking at around 190 mg/g at 30 minutes, as the adsorbent approaches saturation.

Correspondingly, Figure 5.3(b) illustrates the oil removal efficiency (%) for rGO-M. Removal efficiency exhibits a similar trend, rising from 0% at the start to 30% within 1 minute, then sharply increasing to 85% at 5 minutes and ultimately reaching 95% at 30 minutes. This rapid and efficient oil removal demonstrates the practical effectiveness of rGO-M for oil spill remediation in short contact times, a critical factor in emergency clean-up scenarios.

For comparison, Figure 5.3(c) presents the adsorption behaviour of conventionally reduced graphene oxide (rGO). Here, the adsorption capacity is notably lower, with a slower initial increase from 0 mg/g to 30 mg/g within the first minute and a maximum capacity of approximately 120 mg/g after 30 minutes. This suggests slower adsorption kinetics and fewer accessible active sites compared to rGO-M, likely due to differences in surface area and functional group availability introduced during the reduction process.

Figure 5.3(d) displays the oil removal efficiency of rGO, which rises from 0% at the start to 15% at 1 minute, reaching 55% at 5 minutes, and plateauing at 60% at 30 minutes. The comparatively lower removal efficiency and slower adsorption rate highlight the superior performance of rGO-M in both speed and capacity.

Together, these adsorption kinetics and efficiency results underscore the enhanced performance of microwave-reduced graphene oxide over conventional rGO in oil spill remediation. The rapid adsorption kinetics and higher oil uptake capacity of rGO-M can be attributed to its increased surface area, improved porosity, and enhanced hydrophobicity obtained through microwave-assisted reduction. These features facilitate stronger interactions with oil molecules and faster adsorption rates, making rGO-M a highly promising material for efficient and rapid oil spill clean-up [46,47].

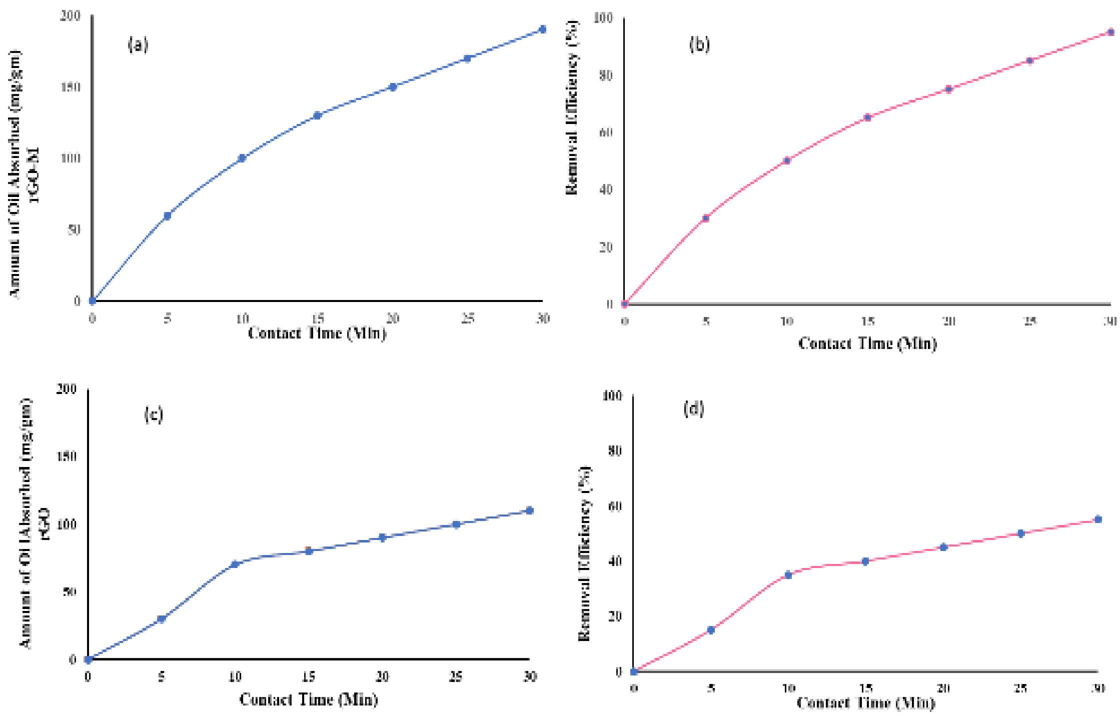

Figure 5.3: Adsorption performance of rGO-M for oil spill remediation (a) oil Adsorbed vs time, (b) Removal efficiency vs time, adsorption performance of rGO for oil spill remediation (c) oil Adsorbed vs time and (d) Removal efficiency vs time.

5.2.4 Optimization of rGO-M synthesis using Box-Behnken Design (BBD)

The synthesis of microwave-reduced graphene oxide (rGO-M) was optimized by analyzing the removal efficiency of pollutants during wastewater treatment using a quadratic response surface model, as presented in Figure 5.4. The model's analysis of variance (ANOVA) results indicate a highly significant fit, with a Model F-value of 30.18 and a p-value less than 0.0001. This significance confirms that the selected factors and their interactions effectively explain the variability observed in pollutant removal efficiency.

The independent variables investigated include microwave power (A), exposure time (B), and reducing agent concentration (C). The model evaluated not only their individual effects but also the interaction terms (AB, AC, BC) and quadratic terms (A^2, B^2, C^2) to capture possible nonlinear relationships. Statistical analysis revealed that microwave power (A), exposure time (B), reducing agent concentration (C), the interaction between exposure time and reducing agent concentration (BC), and the quadratic term for microwave power (A^2) are significant factors influencing removal efficiency, all with p-values below 0.05.

The significant interaction between exposure time and reducing agent concentration (BC) indicates that optimal removal efficiency is achieved through a synergistic balance of these two parameters. Specifically, a moderate reducing agent concentration combined with increased exposure time enhances the pollutant removal capacity of rGO-M. Conversely, interactions between microwave power and exposure time (AB), microwave power and reducing agent concentration (AC), and the quadratic terms for exposure time (B^2) and reducing agent concentration (C^2) were not statistically significant (p-values > 0.10), suggesting their limited influence within the tested parameter ranges.

The robustness and predictive accuracy of the quadratic model are evidenced by strong model fit statistics. The adjusted R^2 value of 0.9426 and the coefficient of determination (R^2) of 0.9749 demonstrate excellent agreement between observed and predicted removal efficiencies. Furthermore, the predicted R^2 value of 0.7835 is in reasonable concordance with the adjusted R^2, indicating reliable model predictions within the experimental design space. The model's precision is supported by a low standard deviation of 1.5409 and a coefficient of variation (C.V.) of 1.726%, reflecting minimal data variability. Additionally, a high signal-to-noise ratio is indicated by the Adequate Precision value of 20.691, substantially exceeding the minimum threshold of 4, confirming the model's suitability for exploring the design space and guiding synthesis optimization.

Three-dimensional response surface plots (Figure 5.4(a–c)) visually demonstrate the effect of microwave power, exposure time, and reducing agent concentration on removal efficiency. These plots illustrate that removal efficiency improves with increasing microwave power and exposure time, particularly when paired with a moderate concentration of reducing agent. Complementary two-dimensional contour plots (Figure 5.4(d–f)) further elucidate the interactions between variables and aid in identifying the optimal conditions for maximizing removal efficiency.

Overall, the model's high significance ($p < 0.001$) and strong statistical indicators provide confidence in the identified factors influencing rGO-M synthesis. These insights enable a targeted approach for optimizing synthesis parameters to enhance the environmental remediation performance of rGO-M (Rakhmatullin et al., 2022).

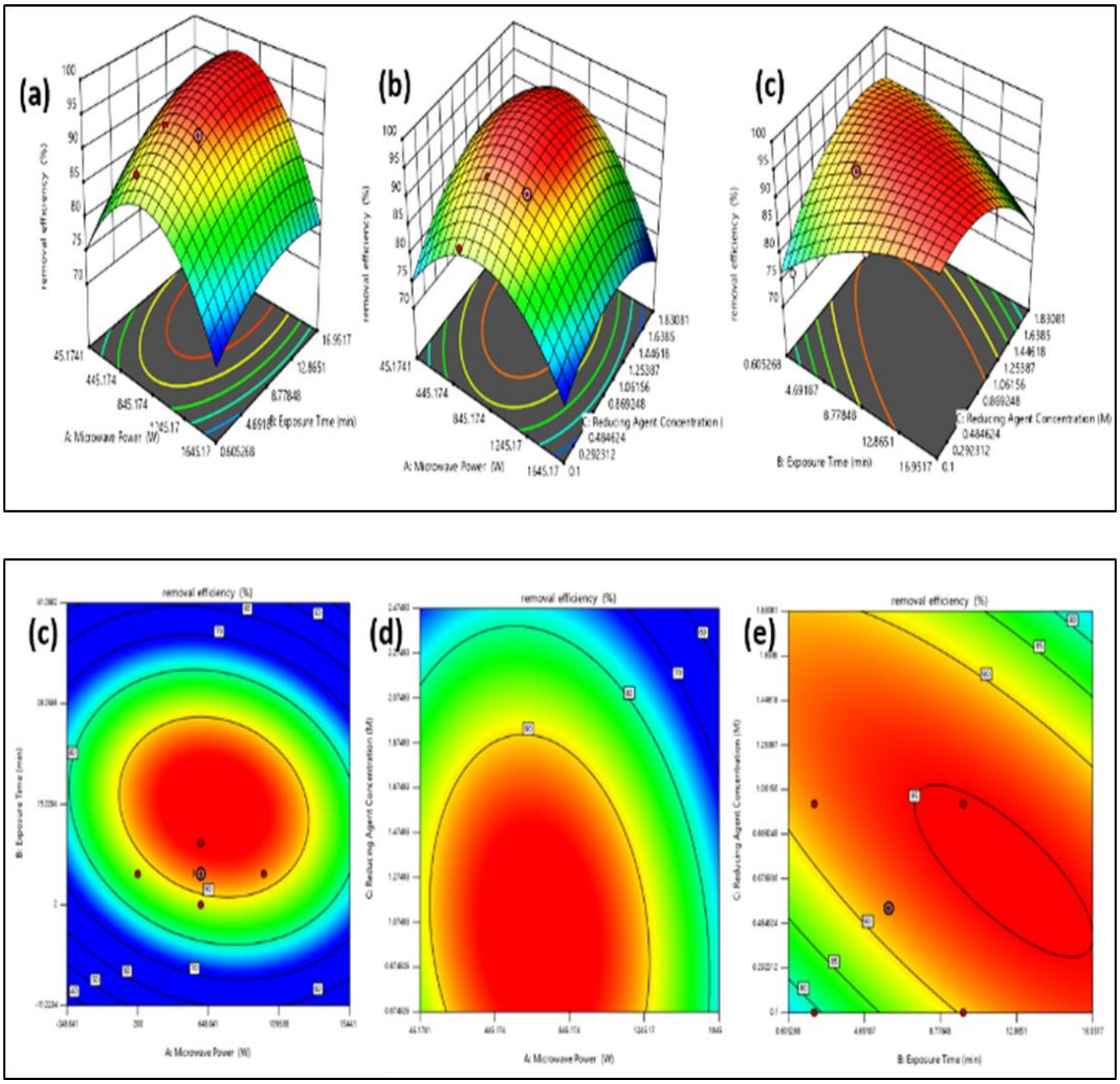

Figure 5.4: (a-c) 3D response surface plots showing the effects of microwave power, exposure time, and reducing agent concentration on removal efficiency. Increasing microwave power and exposure time, with moderate reducing agent concentration, enhances efficiency. (d-f) Contour plots highlighting the interaction effects between the variables, identifying optimal conditions for achieving maximum removal efficiency.

5.3 Mechanism of GO to rGO-M

The transformation of graphene oxide (GO) into microwave-reduced graphene oxide (rGO-M) involves several crucial processes that exploit GO's unique dielectric properties. GO is inherently polar due to its abundant oxygen-containing functional groups, such as hydroxyl, epoxy, and carboxyl groups, which render it responsive to microwave radiation at the commonly used frequency of 2.45 GHz. When exposed to microwave irradiation, these polar groups absorb microwave energy efficiently, leading to selective excitation and localized heating of the oxygen functionalities attached to the graphene basal planes and edges.

This selective heating facilitates the cleavage of carbon-oxygen bonds, effectively removing the oxygen-containing groups and restoring the sp^2 hybridized conjugated carbon network characteristic of graphene (Scholte et al., 1984). The process rapidly breaks down the disrupted carbon lattice caused by oxidation, recovering the electrical conductivity and mechanical integrity of the material. Importantly, the microwave-assisted reduction offers uniform energy distribution throughout the GO sample, as reported by Zhou et al. (2017), ensuring consistent reduction and minimizing localized overheating or incomplete reduction zones. This uniformity is critical to producing high-quality rGO-M with enhanced electrical conductivity and structural homogeneity.

Additionally, the controlled microwave environment significantly suppresses side reactions that commonly occur during conventional thermal reduction, such as the generation of excessive defects or the incorporation of impurities (Mhlongo et al., 2025). By limiting these undesirable pathways, microwave-assisted reduction yields rGO-M with improved surface area and porosity, which directly contribute to its superior adsorption performance. These enhanced surface characteristics make rGO-M particularly well-suited for environmental remediation applications, including pollutant adsorption and oil spill cleanup, where efficient interaction between the adsorbent and contaminants is paramount.

In summary, the mechanism of GO reduction to rGO-M under microwave irradiation relies on the selective and uniform excitation of oxygen-containing groups, rapid bond cleavage, and restoration of the graphene lattice with minimized defect formation. This process produces a high-quality rGO-M material with properties tailored for advanced environmental technologies.

5.4 Conclusion

The microwave-assisted reduction of graphene oxide (GO) to produce reduced graphene oxide (rGO-M) leverages the unique dielectric and polar characteristics of GO to achieve rapid, uniform, and efficient removal of oxygen-containing functional groups. This selective excitation under 2.45 GHz microwave radiation facilitates the restoration of the graphene's conjugated carbon network, enhancing electrical conductivity and structural integrity. Compared to conventional reduction methods, microwave reduction minimizes defect formation and impurity incorporation, resulting in rGO-M with superior surface area and adsorption properties. These improved physicochemical characteristics make rGO-M an ideal candidate for various environmental remediation applications, particularly in pollutant adsorption and oil spill cleanup. Overall, microwave-assisted reduction provides a controlled and scalable approach to synthesizing high-quality rGO materials with enhanced functional performance.

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