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Application of Boron-Doped Reduced Graphene Oxide for the Degradation of Rh B Dye using Adsorption Methods

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Abstract

In the present study, a hydrothermal process was used to fabricate boron-doped reduced graphene oxide (B-rGO) as an adsorbent for the degradation study of Rhodamine B dye. Instrumental analyses such as Scanning Electron Microscopy (SEM), High-Resolution Transmission Electron Microscopy (HRTEM), Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and X-ray Photoelectron Spectroscopy (XPS) were performed to characterise the fabricated adsorbent. The characterisation results validated the effective integration of boron into the graphene oxide framework, hence improving the surface characteristics and adsorption capability with an average particle size of 24 nm. Further, batch adsorption studies were conducted by varying various process parameters such as pH, adsorbent dose, time, and dye concentration. The experiments show 70 percent removal of Rh B at an optimised condition pH 6, adsorbent dose 40 mg/L, contact time 90 min, and dye concentration 10 ppm. Kinetic and isotherm models were fitted to understand the mechanism of the adsorption study. The results show better fitting for the second-order reaction and the Langmuir isotherm model. The findings indicate that B-rGO is a viable material for environmental applications, particularly in wastewater. The research highlights the significance of boron doping in the adsorption properties and stability of reduced graphene oxide.

Keywords
Hydrothermal, Rhodamine B, Boron, Reduced graphene oxide, Adsorption

1. Introduction

Synthetic dyes are extensively utilised in the textile, leather, printing, and allied sectors, resulting in the release of highly pigmented and non-biodegradable effluents into aquatic ecosystems. Rhodamine B, a hydrophilic xanthene dye, is notably concerning owing to its durability, intense fluorescence, and extensive application in textiles, paper, and biological stains, which enhance its environmental persistence and detectability (Shanmuugavel et al.2019).Significantly, RhB is recognised as a possible carcinogen and has been associated with detrimental health impacts, including allergies, respiratory issues, and ecological disturbance (Cheng et al.2019). Conventional wastewater treatment methods frequently prove inadequate for the efficient and affordable removal of RhB (Oladoye et al. 2024). However, the adsorption technique for wastewater treatment had emerged as a potential approach due to its simplicity, high removal efficiency, and ease of implementation (Ahmed et al. 2024). Nowadays, carbon-based nanomaterials, particularly graphene oxide (GO), have garnered considerable interest among adsorbents because to their extensive surface area, diverse surface functionalities, and robust π–π/electrostatic interaction potential with dye molecules (Sahar et al. 2019).

Prior research has established the efficacy of GO and its composites for RhB dye adsorption. Graphene oxide demonstrated a remarkable adsorption affinity for RhB, with the adsorption results aligning closely with the Langmuir isotherm model (Akmal et al. 2025). The thermodynamic characteristics demonstrated that the adsorption process was spontaneous, endothermic, and mostly physisorption, facilitated by electrostatic interactions between the positively charged RhB and negatively charged GO (Cheng et al. 2019).Boron doping in graphene oxide (GO) markedly improves its physicochemical qualities by generating electron-deficient sites, altering the electronic structure, andsurface defects, all of which raise surface area and adsorption capacity. The replacement of carbon atoms in the sp^2 lattice of graphene oxide with boron results in p-type conductivity, generating charge carrier holes and defect sites, hence enhancing adsorbate interactions via Lewis acid–base and electrostatic processes (Alwan et al. 2022).Research indicates that increased boron concentration enhances electrical conductivity and facilitates porosity and surface exfoliation, advantageous characteristics for adsorption applications (Ngidi et al. 2020). Evaluating the adsorption characteristics of RhB onto B-rGO via isotherm models like Langmuir yields an essential understanding of the adsorption mechanism and efficacy. The Langmuir model, which posits monolayer adsorption on uniform binding sites, facilitates the assessment of maximum adsorption capacityand affinity constant. A robust correlation with the Langmuir model often indicates homogeneous surface covering and advantageous adsorption properties. This study aims to illustrate B-rGO's superior adsorption performance compared to pristine GO and conventional adsorbents, establishing a foundation for its application in practical wastewater treatment systems and informing the advancement of next-generation functionalized graphene-based adsorbents.

2. Materials and Methods

2.1Materials

Graphite powder composed of 99per cent graphite, sodium nitrate($NaNO_3$), potassium permanganate ($KMnO_4$), and sulphuric acid (H_2SO_4)waspurchased from Loba Chemie Pvt. Ltd, India. Boric acid was purchased from SRLPvt.Ltd, India. Hydrogen peroxide was purchased from the local market. Deionised water was used throughout the experiments, and all other chemicals and solvents were used without any further purification.

2.2 Synthesis of B-rGO

2.2.1 Synthesis of GO

The GO photocatalyst was synthesised using the modified Hummers approach. 2.0 grams of graphite powder and 1.0 gram of sodium nitrate were incorporated into 46 mL of concentrated sulfuric acid and agitated. Subsequently, 6.0 grams of $KMnO_4$ were introduced to the solution under ice-cold conditions. The solution was agitated at a certain temperature for 30 minutes. 92 mL of deionised water was exclusively added to the aforementioned solution, which was heated for 30 minutes under agitation to eliminate excess $KMnO_4$. Subsequently, H_2O_2 was introduced dropwise into the mixture until no bubbles were detected. The solution was centrifuged, and the sample was washed many times to eliminate the dissolved contaminants. The product underwent freeze-drying [Khan et al. 2026].

2.2.2 Boron-doped ReducedGraphene Oxide

To synthesise boron-doped reduced graphene oxide, the produced graphene oxide was ultrasonically dispersed and mixed with an aqueous boric acid solution in a 1:3 ratio, yielding boron-doped reduced graphene oxide (Khan et al. 2026).

2.2.3 Instrumentation

FT-IR Spectroscopy was used to generate FT-IR (Bruker Optics, GmbH, Germany) spectra of the prepared pure solid sample between the ranges of 4000-400 cm^{-1}. The SEM and TEM were used to examine the morphology of the samples. Using the UV-1780 UV-vis spectrophotometer (Shimadzu), photocatalytic degradation activity was examined with a wavelength range of 200-800 nm. Powder X-ray diffraction experiments were carried out using a PANalytical X'Pert PRO device with Bragg-Brentano geometry (PXRD). XPS study for elemental mapping of the material.

3. Result and Discussion

3.1 Characterisation of B-rGO

The B-rGOused in the present adsorption study has been previously synthesised and comprehensively characterised. Detailed structural and surface analysis, including XRD, FTIR, and XPS, has already confirmed successful boron doping and reduction of graphene oxide. The obtained result verified the formation of a graphitic structure with incorporated boron functionalities and the presence of relevant surface functional groups. The detailed characterisation of B-rGO is already reported in (Khan et al. 2026).

The structural morphology of the B-rGO photocatalyst is shown in Figure 1. The B-rGO samples have a wrinkled, undulated structure, with no variation in surface morphology compared to rGO. The discrepancy arises from the effects of boron doping and deformation during the exfoliation of the carbon framework [Fang et al. 2014].Boron doping led to a reduction in the interlayer spacing (d002 spacing) of graphene oxide, as seen in Figure 1. Figure 2 shows that the Images (b) to (c) demonstrate that the B-rGO samples include randomly aggregated, few-layered ultra-fine sheets that are densely packed. A detailed examination reveals that the nanosheets of B-rGO were aggregated, exhibiting a flake-like morphology. This arose from the thermal annealing of graphene oxide and the reduction of oxygen functional groups, yielding many thin layers of graphene oxide sheets.

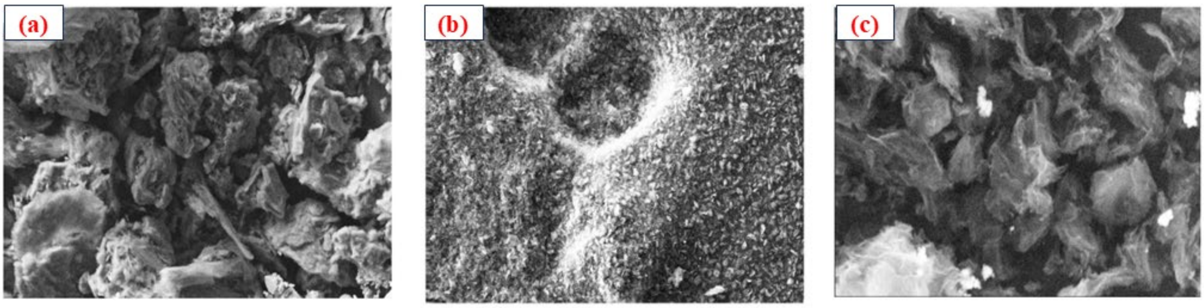

Figure 1. SEM image of (a) graphite, (b) rGO, (c) B-rGO. The image reveals the transformation from the compact, layered structure of graphite to the exfoliated and wrinkled sheet-like morphology of rGO, while B-rGO exhibits a more crumpled, defect-rich and irregular flake-like structure.

The HRTEM microscope of boron-doped rGO reveals a characteristic wrinkled and crumbled sheet-like morphology, which is typical of rGO material. The presence of a few-layer graphene nanosheet with partially transparent regions indicates successful exfoliation and reduction of graphene oxide [Wang et al.2017]. Clear lattice fringes can be observed in certain domains, suggesting the restoration of graphitic crystallinity after the reduction process. The measured interlayer spacing is expected to be close to approximately o.32nm, corresponding to the (002)plane of graphitic carbon, although slight deviation may occur due to boron incorporation and structural defects. Overall,Figure 2 shows the HRTEM image confirms the formation of a few-layered, defect-rich B-rGO nanosheet with partially restored graphitic domains, which are advantageous for RhB removal.

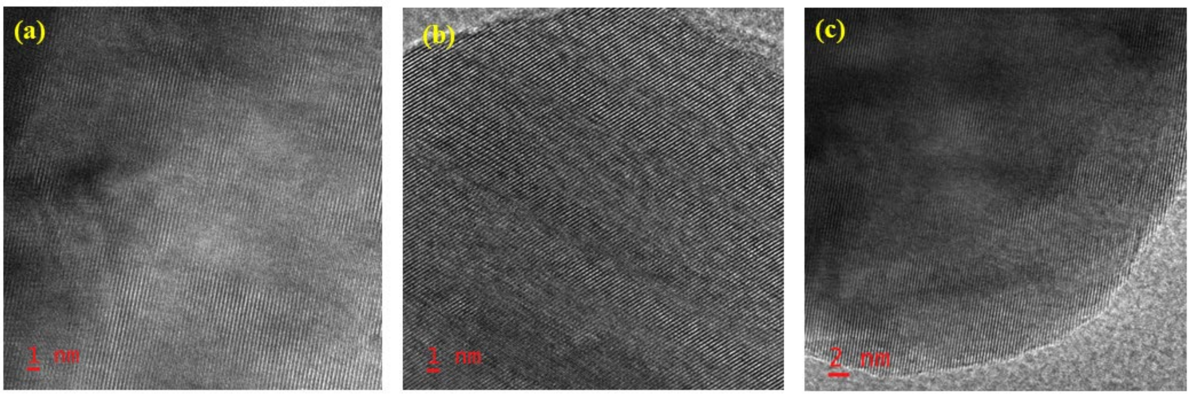

Figure 2. HRTEM image of B-rGO showing few-layered,wrinkled nanosheets with partially restored graphitic lattice fringes and defect-rich domain induced by boron incorporation

4. Batch Adsorption Experiment

Batch adsorption tests were carried out at an initial concentration C_0=10 mg/L, Adsorbent dosage 20 mg/L, pH 6, the sample was withdrawn at predetermined time, filtered, and analysed.

4.1Effect of pH

The removal effectiveness of B-rGOshowed a significant reliance on solution pH throughout the range of 2 to 12. Exhibiting the greatest absorption at pH 6. The bell-shaped curve indicates that adsorption is influenced by the interaction between the surface charge modulation of B-rGO and the speciation or ionic form of the adsorbate.At low pH, significant protonation of oxygen and boron-containing surface functions (e.g.,–OH/–COOH, B–O) and competition from H^+ ions likely inhibit binding.A decrease at elevated pH (10–12) aligns with heightened electrostatic repulsion and/or diminished complexation. Figure 3 of these patterns, pH 6 was designated as the operational pH for the ensuing batch studies.

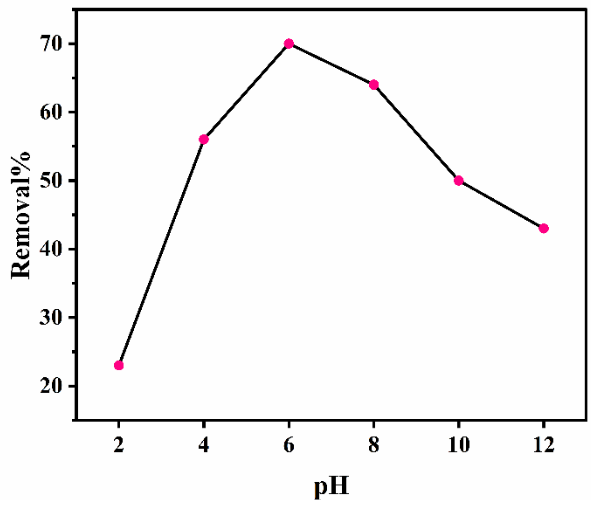

Figure 3. Effect of solution pH on the removal efficiency of Rhodamine B using BrGO. The adsorption efficiency increases with pH, reaching a maximum at pH 6 and subsequently decreases at higher pH values.

4.2 Adsorbent Dosage

The impact of adsorbent dose was examined by meticulous observation of batch adsorption studies utilising an initial dye concentration of 10 mg/L, with the findings illustrated in Figure 4.

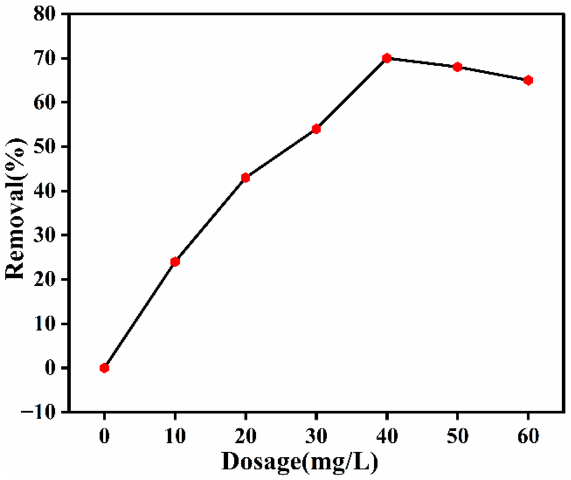

Figure 4. Effect of adsorbent dosage on the removal efficiency of Rhodamine B using B-rGO. Their removal percentage increases with increasing adsorbent dose due to the availability of a greater number of active adsorption sites**.**

The results indicate that the dye removal effectiveness ranged from around 24to 70 percent. The enhancement in removal efficiency can be ascribed to the availability of reactive sites in the reaction, resulting in more dye adsorption. However, increasing the adsorbent quantity to 40 mg resulted in the saturation of the necessary adsorption sites, hence diminishing the adsorbent's influence on adsorption efficiency. Consequently, the ideal adsorbent dose is 40 mg.

5. Kinetic Study

The adsorption kinetics of Rhodamine B onto the B-rGO adsorbent were best described by the pseudo-second order kinetic model, as evidenced by the excellent linear fitting with a correlation coefficient (R^2) of 0.9982. Such a high R^2 value indicates a very strong agreement between the experimental data and the model, confirming that the adsorption process is predominantly governed by chemisorption. This suggests that the rate-limiting step likely involves valence forces through electron sharing or exchange between the functional group of the Rhodamine B molecule and the active site introduced by boron doping on the rGO surface [Gupta and Suhas 2009]. The close fit also implies that the adsorption capacity is dependent on the availability of active binding sites rather than solely on the concentration of the dye in solution. Overall, Figure 5 the kinetic behaviour demonstrates that B-rGO provide highly efficient and chemically interactive adsorption sites for rhodamine B removal, supporting its effectiveness as an advanced adsorbent material.

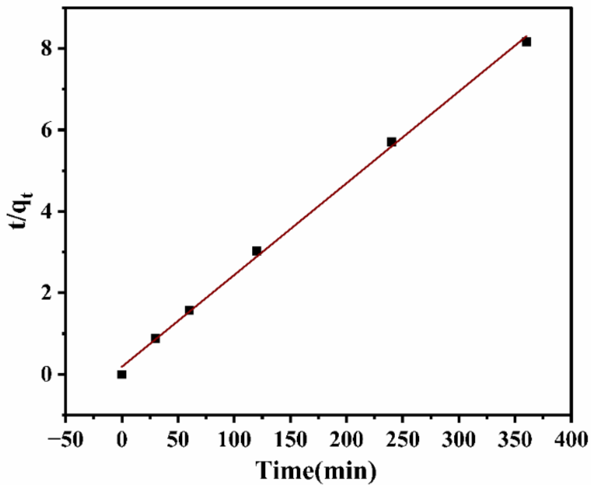

Figure 5. Pseudo-second-order kinetic plot for Rhodamine B adsorption onto boron-doped rGO adsorbent, showing excellent model fit (R^2 = 0.9982), indicating chemisorption-controlled adsorption kinetics.

High surface area and defect state of B-rGO strongly adsorb the rhodamine B dye. In B-rGO, boron doping creates defects and electron-deficient sites, while the rGO surface still contains some oxygen functional groups [Zamani et al. 2020].The rhodamine molecule can attach to B-rGO through (i) π-π stacking between the aromatic rings of Rhodamine B and the sp2 carbon network of rGO, (ii) electrostatic attraction, and (iii) hydrogen bonding with the oxygen group. Boron defect sites can further strengthen binding by providing more chemically active adsorption sites.The Langmuir isotherm means that adsorption occurs mainly as a monolayer. Rhodamine B forms one layer on the surface, and adsorptionstopswhen the available sites are filled. This supports the idea that B-rGO has a finite number of similar adsorption sites, and rhodamine B molecules do not keep forming multiple layers.

6. Equilibrium Isotherm Study

IsothermswerederivedbyalteringC_0 10 mg/L, at fixed dosage and pH, at a constant dosage and pH level. The non-linear Langmuir model [Eq. (1)] and the Freundlich model [Eq. (2)] were fitted using least squares.

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \quad (1)$$

$$q_e = K_f C_e^{1/n} \quad (2)$$

The concentration of RhB was determined using UV-Vis spectrophotometry (Shimadzu UV-2600), with a scan conducted from 200nm to 800 nm. The dye was analysed at a wavelength of 554 nm to determine its maximum adsorption capacity, as indicated by the resulting curve. Throughout the adsorption experiment, the absorbance of the supernatant at 554 nm was assessed using a Shimadzu UV-2600 following the adsorption of each group, in order to ascertain the dye concentration and construct calibration curves based on known dye concentrations, as documented in previous works [Garba and Rahim 2016].

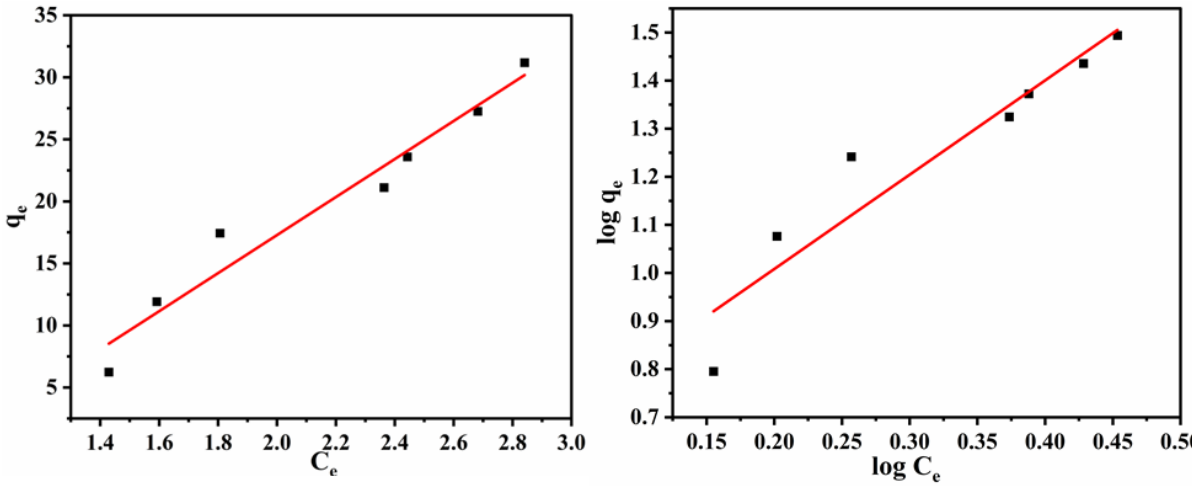

Figure 6. Langmuir and the Freundlich isotherm plot for the adsorption of Rhodamine B onto B-rGO. The linear Langmuir plot exhibits a stronger correlation compared to the Freundlich plot, indicating that the adsorption process is best described by the Langmuir isotherm model.

Compared to the Freudenberg isotherm (0.89823), the Langmuir isotherm has anR^2 value of 0.97725 (Figure 6), which is closer to 1. Thus, it was concluded that the Langmuir isotherm model more adequately characterised the adsorption process. The fact that the adsorption was monolayer-on-homogeneous further indicates this.The maximal adsorption capacity is 50.23 mg/g, as determined by the Langmuir model.The results of the current investigation show that the B-rGO adsorbents perform extremely well. It's obvious that B-rGO is a great adsorbent material for RhBdye wastewater treatment because of its rapid and high yield (Table 1).

Table 1. Adsorption of Dye on Carbon-Based Material

Adsorbent	**Synthesis process**	**Type of dye**	**Removal efficiency**	**Reference**
MgFe2O4/Reduced graphene	Sol-gel and Ultrasonication	Methylene blue	75 %	Adel et al. 2021
Co-MOF@CNT	In-situ solvothermal	Methyl Orange	72%	Qasem et al. 2020
Graphene oxide	Modified Hummer method	Rhodamine B	---	Yin et al. 2019
B-rGO	Reduction method	Rhodamine B	70%	This work

7. Conclusion

The present study successfully demonstrated the synthesis and application of boron-doped rGO as an efficient adsorbent for the removal of Rhodamine B dye from aqueous solution. A batch adsorption experiment revealed that a maximum removal efficiency of 70per cent was achieved at pH 6, an adsorbent dosage of 40 mg/L, and an initial dye concentration of 10 mg/L. The adsorption kinetics were best described by the pseudo-second order model (R^2 = 0.998, indicating chemisorption as the dominant mechanism, while the Langmuir isotherm model R^2= 0.97725 suggested monolayer adsorption on a homogeneous active site with a maximum adsorption capacity of 50.23 mg/g. The enhanced adsorption performance is attributed to ππ interaction, electrostatic attraction, hydrogen bonding, and the presence of electron-deficient boron-induced defect sites. B-rGO is a promising and effective adsorbent for dye-contaminated wastewater treatment.

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