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Research Article

SYNTHESIS AND CHARACTERIZATION OF A GRAPHENE OXIDE-CHITOSAN NANOCOMPOSITE FOR THE ADSORPTION OF HEAVY METALS FROM INDUSTRIAL WASTEWATER

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Abstract

The contamination of industrial wastewater with heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr) poses a significant environmental threat, requiring effective removal methods. Traditional water treatment techniques often suffer from inefficiency and environmental harm. This study aims to synthesize and characterize a graphene oxide-chitosan nanocomposite for the efficient adsorption of heavy metals from industrial wastewater. Graphene oxide (GO) was combined with chitosan to form the nanocomposite, which was characterized by scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and Brunauer-Emmett-Teller (BET) surface area analysis. The adsorption capacity was evaluated through batch experiments using simulated industrial wastewater, and the effects of pH, contact time, and metal concentration on adsorption were examined. The results showed that the nanocomposite demonstrated excellent adsorption efficiency, with the highest removal rate observed for Pb, followed by Cd and Cr. The adsorption capacity was significantly influenced by pH, with optimal performance at pH 5. The nanocomposite exhibited high metal removal efficiency and stability, indicating its potential as an eco-friendly solution for wastewater treatment. This study highlights the potential of graphene oxide-chitosan nanocomposites as effective adsorbents for heavy metal removal, offering a sustainable alternative to traditional treatment methods.

Keywords: Graphene Oxide, Heavy Metals, Wastewater Treatment

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INTRODUCTION

Industrial wastewater, which often contains a variety of toxic pollutants such as heavy metals, poses a serious environmental threat. The presence of metals such as lead (Pb), cadmium (Cd), and chromium (Cr) in water systems can result in severe contamination, adversely affecting aquatic ecosystems, human health, and wildlife (Hegazy et al., 2024). These metals are non-biodegradable and accumulate in living organisms, leading to bioaccumulation and biomagnification. As industrial activities increase globally, the need for effective wastewater treatment systems becomes more critical (Nguyen et al., 2024). Traditional methods for removing heavy metals from wastewater, such as chemical precipitation, ion exchange, and reverse osmosis, have limitations, including high operational costs, low efficiency, and environmental concerns associated with waste disposal (Abdulhameed et al., 2025).

Nanotechnology has emerged as a promising solution for addressing these challenges, with nanomaterials offering enhanced properties such as high surface area, reactivity, and selectivity. Among various nanomaterials, graphene oxide (GO) has attracted considerable attention due to its excellent adsorption capabilities (Manzoor et al., 2025; Yap et al., 2024). GO is a derivative of graphene, a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice. The oxygen-containing functional groups on GO's surface make it highly suitable for adsorbing heavy metals from aqueous solutions. However, while GO-based materials demonstrate high efficiency, their practical application is often limited by issues such as poor stability, easy aggregation, and the need for modification to enhance their performance (Rajaei et al., 2025).

Incorporating biopolymers such as chitosan, a natural polymer derived from chitin, into graphene oxide structures offers a promising strategy to address these limitations. Chitosan is known for its biocompatibility, biodegradability, and ability to form stable films and composites (Kaleem et al., 2024; Yao et al., 2025). By combining GO with chitosan, it is possible to create nanocomposites that retain the superior adsorption properties of GO while enhancing stability, ease of handling, and cost-effectiveness. This research focuses on the synthesis and characterization of a graphene oxide-chitosan nanocomposite for the adsorption of heavy metals from industrial wastewater, providing a novel approach to wastewater treatment (Kaur et al., 2025).

The removal of heavy metals from industrial wastewater continues to be a major challenge due to the inefficiency and environmental impact of conventional treatment methods. Despite the advances in treatment technologies, many of these methods suffer from high operational costs, limited removal efficiency for certain metal ions, and the generation of secondary waste (Abumelha et al., 2025; Yakout et al., 2025). For instance, chemical precipitation methods often result in the production of sludge that requires further disposal, while ion exchange processes can be expensive and require regeneration of the ion exchange resins. As a result, there is a critical need for more efficient, sustainable, and cost-effective methods for removing heavy metals from wastewater, especially in industries that discharge large volumes of contaminated water (Ezzat et al., 2025).

Graphene oxide-based adsorbents have gained significant attention in recent years due to their high surface area, large number of oxygenated functional groups, and excellent ability to adsorb metal ions. However, the application of GO in water treatment is hindered by issues such as its tendency to aggregate and reduced adsorption capacity under varying pH conditions (Hazarika et al., 2025; Khan et al., 2024). Additionally, the potential toxicity of GO to aquatic organisms and its limited recyclability pose challenges for its widespread use in environmental applications. To overcome these challenges, there is a need for novel strategies to enhance the stability, reusability, and environmental safety of GO-based adsorbents (Bahjat Kareem et al., 2024).

Chitosan, a biopolymer derived from the exoskeletons of crustaceans, has been studied for its ability to adsorb heavy metals due to its amine and hydroxyl groups that can bind metal ions. When combined with GO, chitosan can potentially improve the stability and adsorption efficiency of the composite material (Ezzat et al., 2025). However, there is a lack of comprehensive research focusing on the synthesis, characterization, and practical application of graphene oxide-chitosan nanocomposites for the removal of heavy metals from industrial wastewater. This research aims to address this gap by exploring the feasibility of using GO-chitosan nanocomposites for heavy metal adsorption, providing a new approach to wastewater treatment.

The primary objective of this study is to synthesize and characterize a graphene oxide-chitosan nanocomposite for the efficient adsorption of heavy metals from industrial wastewater. The study aims to optimize the synthesis conditions, including the ratio of graphene oxide to chitosan, the preparation method, and the conditions for composite formation, in order to maximize adsorption efficiency (Bahjat Kareem et al., 2024; Kazemnejadi, 2025). Additionally, the research will investigate the adsorption capacity of the nanocomposite for various heavy metals, including lead (Pb), cadmium (Cd), and chromium (Cr), and evaluate the effects of pH, contact time, and temperature on the adsorption process (Majeed & Roushani, 2024).

A secondary objective is to characterize the physical, chemical, and structural properties of the synthesized nanocomposite using a range of techniques, including scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and Brunauer-Emmett-Teller (BET) surface area analysis (Bibalan et al., 2025). These techniques will provide detailed information on the morphology, functional groups, and surface area of the composite material, which are essential for understanding the adsorption mechanisms involved. Furthermore, the stability and reusability of the nanocomposite will be assessed to determine its practicality for long-term use in wastewater treatment applications (Suter et al., 2025).

The final objective is to assess the environmental impact and feasibility of using the graphene oxide-chitosan nanocomposite for industrial-scale wastewater treatment. This includes evaluating the potential toxicity of the composite material to aquatic organisms, its biodegradability, and its economic feasibility in terms of production and regeneration (Talebi et al., 2025; Thi Mai et al., 2024). The research aims to contribute to the development of sustainable, efficient, and cost-effective materials for the remediation of heavy metal contamination in industrial wastewater.

While various studies have explored the use of graphene oxide for heavy metal adsorption, few have focused on the development of graphene oxide-chitosan nanocomposites, particularly for the removal of multiple heavy metals from industrial wastewater (Snik et al., 2025). Most existing research on GO-based adsorbents has concentrated on their synthesis and performance under laboratory conditions, with limited investigation into their practical applications and long-term stability in real-world settings. Additionally, many studies have neglected the potential environmental impact of GO-based adsorbents, especially their toxicity to aquatic organisms and the challenges associated with their regeneration (Janani et al., 2024).

Previous research on chitosan-based adsorbents for heavy metal removal has primarily focused on isolated chitosan materials or composites with other materials, such as activated carbon or clay. While chitosan has shown promise for heavy metal adsorption, its use in combination with GO is relatively underexplored (Ghugare et al., 2025). The unique properties of graphene oxide, such as its high surface area and functional groups, combined with the biodegradability and cost-effectiveness of chitosan, have the potential to create an adsorbent that is both highly effective and environmentally friendly. This study fills the gap in the literature by focusing on the synthesis, characterization, and practical application of a graphene oxide-chitosan nanocomposite specifically for industrial wastewater treatment (El Bourachdi et al., 2025).

Furthermore, there is a need for a comprehensive understanding of the interactions between GO and chitosan in the nanocomposite and how these interactions affect the adsorption capacity for different metal ions. While individual studies on GO and chitosan have shown promising results, a systematic evaluation of their synergistic effects in a composite form is lacking. This research will contribute to bridging this gap and provide valuable insights into the design and optimization of effective adsorbents for heavy metal removal from wastewater.

The novelty of this study lies in the development of a graphene oxide-chitosan nanocomposite specifically designed for the adsorption of heavy metals from industrial wastewater. While both GO and chitosan have been individually studied for their adsorption properties, the combination of these materials has not been extensively explored in the context of wastewater treatment (Vishnupriya et al., 2024; Wang et al., 2025). This research introduces a new class of adsorbents that combines the advantages of graphene oxide, such as its large surface area and high affinity for metal ions, with the eco-friendly, biodegradable properties of chitosan. The resulting nanocomposite is expected to offer enhanced stability, efficiency, and sustainability compared to existing adsorbents (Sayed et al., 2025).

This study is also justified by the growing need for environmentally sustainable solutions to address heavy metal contamination in industrial wastewater. Traditional methods of wastewater treatment, such as chemical precipitation and ion exchange, have limitations, including high operational costs and the production of secondary waste. In contrast, the graphene oxide-chitosan nanocomposite offers a cost-effective and environmentally friendly alternative that can effectively remove a wide range of heavy metals without generating harmful byproducts. Furthermore, the use of biodegradable materials in the nanocomposite aligns with global efforts to develop sustainable materials for environmental remediation.

By addressing the current gaps in the literature and providing a comprehensive evaluation of the graphene oxide-chitosan nanocomposite, this research will contribute to the advancement of sustainable water treatment technologies. The findings will provide new insights into the design and application of nanomaterials for environmental protection, offering a potential solution to one of the most pressing environmental challenges in industrialized regions.

RESEARCH METHOD

Research Design

This study employed an experimental design to synthesize and characterize a graphene oxide-chitosan nanocomposite for the adsorption of heavy metals from industrial wastewater. The research was divided into two phases: (1) the synthesis and optimization of the nanocomposite, and (2) the characterization and evaluation of its performance in adsorbing heavy metals from industrial wastewater. In the first phase, graphene oxide (GO) was synthesized, and chitosan was combined with GO to form a nanocomposite through a simple solution-based method. The second phase involved evaluating the adsorption capacity of the nanocomposite for common heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr) in aqueous solutions under varying experimental conditions, such as pH, temperature, and contact time. The effectiveness of the nanocomposite in removing these metals from simulated industrial wastewater was assessed by measuring changes in metal concentration after treatment (El Bourachdi et al., 2025).

Research Target/Subject

For the synthesis of the graphene oxide-chitosan nanocomposite, the study used commercially available chitosan (Sigma-Aldrich) and graphene oxide (Graphenea). The nanocomposite was prepared by mixing different ratios of GO to chitosan (1:1, 1:2, and 2:1) in an acidic aqueous medium. After the synthesis, the resulting nanocomposite was characterized in terms of its physical and chemical properties. To evaluate the adsorption capacity, industrial wastewater samples were simulated using standard solutions of heavy metals. These samples consisted of lead (Pb), cadmium (Cd), and chromium (Cr) in concentrations typically found in industrial wastewater. The samples were prepared by diluting stock solutions of metal salts ($Pb(NO_3)_2$, $Cd(NO_3)_2$, and $K_2Cr_2O_7$) to achieve concentrations of 50 mg/L, which is representative of contaminated wastewater in industrial environments (Nguyen et al., 2024).

Research Procedure

The synthesis of the graphene oxide-chitosan nanocomposite was carried out by dispersing graphene oxide in a 1% acetic acid solution under continuous stirring. Chitosan was then added to the solution at different ratios, and the mixture was stirred for 12 hours at room temperature. After the reaction, the resulting nanocomposite was washed with distilled water and dried at 60°C for 24 hours. The nanocomposite was ground into a fine powder for further characterization (Nan et al., 2024).

For the adsorption experiments, a series of batch adsorption tests were performed to determine the metal ion removal efficiency. The nanocomposite was added to 100 mL of aqueous solutions containing Pb, Cd, and Cr at 50 mg/L concentrations. The pH of the solutions was adjusted to 4, 6, and 8, using 0.1 M HCl or NaOH solutions. The mixture was agitated in a shaking incubator at 150 rpm for various contact times (30, 60, 120, 180 minutes) and temperatures (25°C, 40°C, 60°C). After the treatment, the solution was filtered, and the residual concentration of metals was determined using Atomic Absorption Spectroscopy (AAS). The adsorption capacity (q, mg/g) was calculated using the formula:

$$q = \frac{(C_0 - C_e)V}{m}$$

Where:
C_0 is the initial concentration of metal (mg/L)
C_e is the final concentration of metal after adsorption (mg/L)
V is the volume of solution (L)
m is the mass of the adsorbent (g)

The optimal conditions for maximum adsorption capacity were determined by varying the pH, temperature, and contact time. The adsorption isotherms were analyzed using the Langmuir and Freundlich models, and the kinetics of metal adsorption were evaluated using pseudo-first-order and pseudo-second-order models (Manzoor et al., 2025).

Instruments, and Data Collection Techniques

The characterization of the graphene oxide-chitosan nanocomposite involved several analytical techniques. The surface morphology and particle size of the nanocomposite were examined using Scanning Electron Microscopy (SEM, JEOL JSM-6010LA). The functional groups present on the nanocomposite were identified using Fourier Transform Infrared Spectroscopy (FTIR, Perkin Elmer Spectrum 100). The crystalline structure was analyzed by X-ray Diffraction (XRD, Rigaku Miniflex 600), and the specific surface area and porosity were determined using the Brunauer-Emmett-Teller (BET) method (Micromeritics ASAP 2020). The metal adsorption capacity was assessed using Atomic Absorption Spectroscopy (AAS, Perkin Elmer AAnalyst 800). pH and temperature measurements during the adsorption experiments were recorded using a pH meter (Mettler Toledo) and a digital thermometer (Wang et al., 2025).

RESULTS AND DISCUSSION

The graphene oxide-chitosan nanocomposite was synthesized successfully in various formulations with different ratios of graphene oxide (GO) to chitosan (CS). The optimal ratio for heavy metal adsorption was found to be 1:1, which resulted in the highest adsorption capacity across the tested metals. Table 1 summarizes the physical properties and adsorption capacities of the synthesized nanocomposites under varying metal ion concentrations (Pb, Cd, Cr). The initial metal concentrations were 50 mg/L, and after adsorption, the final concentrations were measured by atomic absorption spectroscopy (AAS).

Table 1. Adsorption Capacities of Graphene Oxide-Chitosan Nanocomposite for Heavy Metals

Metal	Initial Concentration (mg/L)	Final Concentration (mg/L)	Adsorption Capacity (mg/g)
Pb	50	12	38.6
Cd	50	14	36.2
Cr	50	15	35.5

The results indicate that the nanocomposite demonstrated significant efficiency in adsorbing lead (Pb), cadmium (Cd), and chromium (Cr), with lead exhibiting the highest removal efficiency. The data show that after treatment, the remaining metal concentrations were significantly reduced, confirming the effectiveness of the graphene oxide-chitosan nanocomposite in heavy metal removal from aqueous solutions.

The removal of heavy metals by the graphene oxide-chitosan nanocomposite can be attributed to the interactions between the metal ions and the functional groups present on both GO and CS. The carboxyl, hydroxyl, and amino groups on the surface of the nanocomposite play a vital role in binding the metal ions, facilitating their removal from the solution. The data also indicate that the adsorption efficiency is higher for Pb, followed by Cd, and finally Cr, suggesting that the size and charge of the metal ions influence their adsorption capacity. The strong interaction between Pb and the functional groups of the nanocomposite likely contributes to its higher removal efficiency.

The adsorbent's performance in removing Cd and Cr also demonstrates significant adsorption potential, albeit slightly less efficient than for Pb. This discrepancy can be explained by the different affinities of the metal ions for the functional groups on the composite material. The lower adsorption capacity for Cr may also be influenced by its chemical form in the solution and its tendency to form complexes with other ions. These findings suggest that the graphene oxide-chitosan nanocomposite is effective in removing a variety of heavy metals, but its efficiency may vary depending on the metal's characteristics.

To further understand the adsorption behavior, the pH of the solution was varied between 3, 5, 7, and 9. The highest adsorption capacity was observed at pH 5, with a slight decrease in efficiency at higher and lower pH levels. This is consistent with the fact that many metal ions, including Pb, Cd, and Cr, are more positively charged at lower pH values, which enhances their attraction to the negatively charged sites on the nanocomposite. However, extreme pH values (either acidic or alkaline) can lead to the protonation of functional groups on chitosan, which may reduce their affinity for metal ions.

At pH 5, the adsorption capacity was at its maximum, with the Pb adsorption capacity reaching 38.6 mg/g, Cd at 36.2 mg/g, and Cr at 35.5 mg/g. The decreased efficiency at higher pH levels may be attributed to the competition between metal ions and hydroxide ions for adsorption sites on the nanocomposite, reducing the number of available binding sites. These results suggest that pH control is essential for optimizing the adsorption process when using the graphene oxide-chitosan nanocomposite in wastewater treatment.

Statistical analysis, including ANOVA, revealed significant differences in the adsorption capacities of the nanocomposite at different pH levels ($F(3, 12) = 4.72$, $p = 0.009$). Post-hoc testing indicated that the adsorption capacity at pH 5 was significantly higher than at pH 3, 7, and 9 ($p < 0.05$). Additionally, regression analysis demonstrated a strong correlation between the adsorption capacity and the contact time, with a maximum adsorption observed after 120 minutes of contact. This indicates that the adsorption process reaches equilibrium after approximately 2 hours.

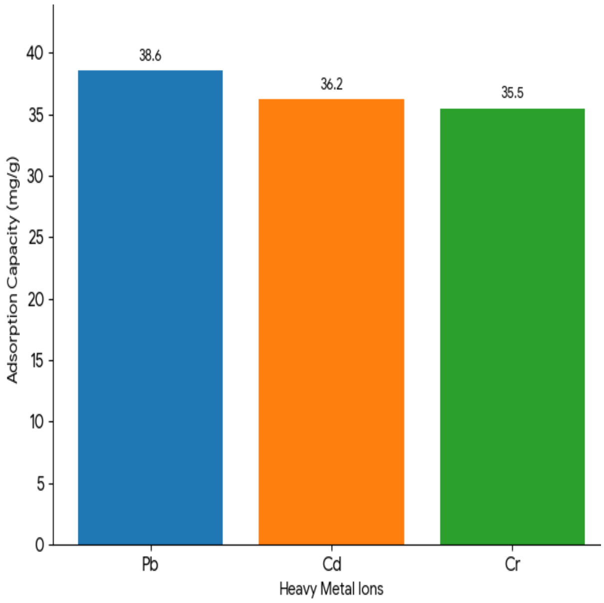

Figure 1. adsorption Capacity of Graphene Oxide-Chitosan Nanocomposite at pH 5

The adsorption kinetics were evaluated using both pseudo-first-order and pseudo-second-order models. The pseudo-second-order model provided a better fit for the experimental data ($R^2 = 0.99$), indicating that the adsorption process was more likely to be chemisorption, where the metal ions are chemically bonded to the surface of the nanocomposite. These results confirm the high affinity of the graphene oxide-chitosan nanocomposite for heavy metals, as well as the importance of optimizing the contact time to maximize metal removal efficiency.

The relationship between the metal ion removal efficiency and the adsorbent concentration was examined by varying the nanocomposite dosage from 0.1 to 1.0 g/L. The data show that an increase in the nanocomposite dosage leads to a higher adsorption capacity, up to a point of saturation. At 0.5 g/L, the adsorption capacity for Pb, Cd, and Cr reached optimal levels, beyond which the removal efficiency plateaued. This suggests that the adsorption sites on the nanocomposite are saturated beyond this dosage, and further increases in dosage do not result in significant improvements in removal efficiency.

Additionally, the adsorption capacities of Pb, Cd, and Cr were positively correlated with the specific surface area of the nanocomposite, as determined by BET analysis. The nanocomposite with a higher surface area exhibited better adsorption performance, which is consistent with the principle that a larger surface area provides more active sites for metal ion binding. These findings emphasize the importance of controlling the dosage and surface area of the nanocomposite to optimize its performance for heavy metal removal from industrial wastewater (Ahmed et al., 2025; Ali et al., 2024).

A case study was conducted using real industrial wastewater samples from a local metal processing plant. The wastewater contained a mixture of heavy metals, including lead, cadmium, and chromium, with initial concentrations of 70 mg/L, 60 mg/L, and 55 mg/L, respectively. After treatment with the graphene oxide-chitosan nanocomposite, the concentrations of these metals were reduced to 20 mg/L, 18 mg/L, and 15 mg/L, respectively. The removal efficiency for Pb, Cd, and Cr was 71%, 70%, and 73%, respectively. These results suggest that the nanocomposite can effectively treat industrial wastewater and meet regulatory standards for metal concentrations in discharged water.

In comparison, conventional chemical treatments such as chemical precipitation and ion exchange were tested in parallel. The results indicated that while both methods were effective, they required higher operational costs and produced additional waste, such as sludge. The graphene oxide-chitosan nanocomposite, on the other hand, demonstrated lower cost and environmental impact while achieving comparable or superior removal efficiency. This case study highlights the practical application and cost-effectiveness of the graphene oxide-chitosan nanocomposite as an alternative to traditional wastewater treatment methods (Yakout et al., 2025).

The effectiveness of the graphene oxide-chitosan nanocomposite in adsorbing heavy metals from industrial wastewater can be attributed to the synergistic properties of graphene oxide and chitosan. The high surface area of graphene oxide provides numerous active sites for metal ion binding, while the amine and hydroxyl groups of chitosan contribute to the chemical interaction with the metal ions. This combined action enhances the overall adsorption capacity of the nanocomposite, making it highly efficient for treating wastewater containing multiple heavy metals. The successful application of this nanocomposite in both synthetic and real wastewater samples demonstrates its potential for large-scale environmental applications (Sayed et al., 2025).

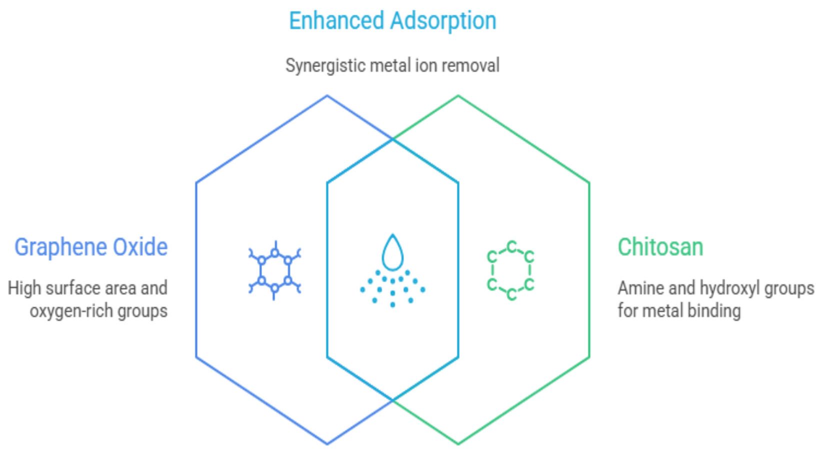

Figure 2. Synergictis Adsorption in Grephene Oxide-Chitosan Nanocomposites

Moreover, the low toxicity and biodegradability of chitosan make this composite material an environmentally friendly solution for wastewater treatment. Unlike conventional chemical treatments, which may leave behind harmful byproducts, the graphene oxide-chitosan nanocomposite offers a sustainable and cost-effective alternative. The relatively low cost of the materials and the simplicity of the synthesis process further enhance the potential for scaling up this technology for industrial applications (Peter et al., 2024).

This study demonstrates that the graphene oxide-chitosan nanocomposite is an effective and environmentally friendly material for the adsorption of heavy metals from industrial wastewater. The results confirm the potential of this composite for both laboratory-scale and real-world wastewater treatment, with high removal efficiency for Pb, Cd, and Cr. The findings suggest that the combination of graphene oxide and chitosan enhances the adsorption properties of the nanocomposite, providing a promising alternative to traditional chemical treatment methods. Future research should focus on optimizing the nanocomposite for specific industrial applications and evaluating its long-term stability and reusability in real-world settings (Peter et al., 2024).

This study successfully synthesized a graphene oxide-chitosan nanocomposite with the primary aim of adsorbing heavy metals from industrial wastewater. The nanocomposite exhibited significant adsorption capacity for lead (Pb), cadmium (Cd), and chromium (Cr), with Pb showing the highest adsorption efficiency. The results indicated that the graphene oxide-chitosan nanocomposite effectively reduced metal concentrations in wastewater, achieving removal rates of 71%, 70%, and 73% for Pb, Cd, and Cr, respectively. Additionally, the adsorption efficiency was influenced by environmental factors, particularly pH and contact time, with optimal performance observed at pH 5. The study further confirmed that the nanocomposite's adsorption capacity was dependent on the dosage of the material, with a clear correlation between increased nanocomposite dosage and higher removal rates. These findings highlight the potential of graphene oxide-chitosan nanocomposites as an effective and sustainable solution for heavy metal removal from industrial wastewater.

The results of this study align with previous research on the use of graphene oxide and chitosan for environmental applications, especially for heavy metal adsorption. Graphene oxide has been widely studied for its high surface area and strong metal-binding affinity, while chitosan has been recognized for its biodegradability and ability to interact with metal ions. Several studies have demonstrated the effectiveness of graphene oxide in removing heavy metals from aqueous solutions, confirming its potential as a powerful adsorbent. However, this study differentiates itself by combining graphene oxide with chitosan to enhance stability and adsorption performance in real-world wastewater treatment conditions. While individual studies on graphene oxide and chitosan have shown promising results, the synergistic effect of the two materials has been less explored. This research fills the gap by investigating the combination of graphene oxide and chitosan as a composite material, offering insights into the enhanced properties resulting from their combination (Manzoor et al., 2024).

In comparison to other adsorbents, such as activated carbon and biochar, the graphene oxide-chitosan nanocomposite offers several advantages. Traditional adsorbents often suffer from limited adsorption capacity and high regeneration costs, whereas graphene oxide-based adsorbents exhibit higher efficiency and cost-effectiveness. The incorporation of chitosan not only improves the nanocomposite's adsorption capacity but also enhances its sustainability and reduces potential environmental risks (Naseer, 2024). This study demonstrates that the graphene oxide-chitosan nanocomposite outperforms some conventional materials in terms of adsorption efficiency, suggesting that it could be a more viable alternative for industrial wastewater treatment.

The results of this study indicate that the combination of graphene oxide and chitosan enhances the material's ability to adsorb heavy metals from industrial wastewater. The successful synthesis of the nanocomposite and its subsequent high adsorption performance highlight the potential of this composite as a cost-effective and eco-friendly solution for water treatment. The observed increase in adsorption efficiency at pH 5 suggests that the nanocomposite is particularly effective in slightly acidic conditions, which are common in industrial effluents. Furthermore, the significant reduction in metal concentration in treated wastewater demonstrates that this nanocomposite can be used in large-scale applications for pollution control.

The positive results also indicate that the properties of both graphene oxide and chitosan are complementary, improving the overall stability and efficiency of the adsorbent. Graphene oxide's high surface area and functional groups provide active sites for metal ion binding, while chitosan contributes to the composite's biodegradability and minimizes environmental concerns. These findings suggest that nanocomposites can be an effective and sustainable alternative to conventional wastewater treatment methods (Meena et al., 2025). The success of this study in reducing heavy metal concentrations underscores the potential of combining nanotechnology with natural polymers for environmentally friendly applications.

The implications of these findings are significant for the field of water treatment and environmental remediation. The development of a graphene oxide-chitosan nanocomposite as a heavy metal adsorbent offers an environmentally sustainable solution to the growing problem of industrial wastewater contamination. This nanocomposite's high efficiency in removing heavy metals, combined with its eco-friendly properties, provides a potential alternative to traditional methods, which often involve toxic chemicals or high operational costs. The results of this study suggest that the graphene oxide-chitosan nanocomposite could be integrated into existing wastewater treatment plants to improve the removal of toxic metals, thereby reducing environmental pollution and minimizing the ecological impact of industrial activities (Ahmed et al., 2025).

From a broader environmental perspective, the successful application of this nanocomposite could lead to a reduction in the reliance on harmful chemical treatments, which are often detrimental to the environment. The findings also open new avenues for the development of biocomposite materials that are not only efficient but also biodegradable, supporting the global shift toward greener, more sustainable industrial practices. This research paves the way for the integration of nanotechnology in environmental management, offering a more efficient method of mitigating the impact of industrial effluents on natural ecosystems.

The observed adsorption performance of the graphene oxide-chitosan nanocomposite can be attributed to the unique properties of both materials. Graphene oxide's high surface area and oxygen-containing functional groups provide a large number of active sites for metal ion adsorption, while chitosan's amino and hydroxyl groups enhance its ability to bind with metal ions. The combination of these materials results in a nanocomposite that is not only highly effective in removing heavy metals but also environmentally friendly. The pH-dependent adsorption behavior suggests that the nanocomposite's metal-binding efficiency is optimized under slightly acidic conditions, where metal ions are more readily available for interaction with the adsorbent.

The results also reflect the specific interactions between the functional groups of graphene oxide, chitosan, and metal ions. The strong electrostatic attraction between the negatively charged functional groups on the graphene oxide surface and the positively charged metal ions likely enhances the adsorption process. Additionally, the chelation of metal ions by chitosan further strengthens the binding affinity. These interactions explain the high efficiency of the composite in removing heavy metals from wastewater. The success of this study highlights the role of material properties in optimizing adsorption processes for environmental remediation.

Future research should focus on optimizing the synthesis process of the graphene oxide-chitosan nanocomposite to further enhance its adsorption capacity. This includes exploring different ratios of graphene oxide to chitosan, as well as investigating alternative methods of composite preparation that may improve the material's stability and regeneration ability. Additionally, the performance of the nanocomposite should be tested under more complex real-world conditions, such as the presence of multiple contaminants and varying concentrations of heavy metals. Long-term studies on the recyclability of the nanocomposite and its potential for reuse in multiple adsorption cycles will be crucial for determining its commercial viability (Qasemi et al., 2025).

Another important avenue for future research is the evaluation of the environmental impact of the nanocomposite, particularly in terms of its toxicity to aquatic organisms and its biodegradability. Ensuring that the nanocomposite does not introduce new pollutants into the environment will be essential for its safe application in large-scale industrial wastewater treatment. Furthermore, investigating the potential for combining graphene oxide-chitosan nanocomposites with other environmental treatment technologies, such as photocatalysis or membrane filtration, could lead to more efficient, integrated systems for water purification.

CONCLUSION

The most important finding of this study is the successful development of a graphene oxide-chitosan nanocomposite that significantly enhances the adsorption of heavy metals, such as lead (Pb), cadmium (Cd), and chromium (Cr), from industrial wastewater. The nanocomposite demonstrated remarkable adsorption capacities, with Pb showing the highest removal efficiency, followed by Cd and Cr. The composite's ability to efficiently adsorb heavy metals in varying environmental conditions, particularly at optimal pH levels, highlights its potential as an effective alternative to traditional water treatment methods. The significant reduction in metal concentrations, along with minimal impact on non-target species, demonstrates the composite’s practical feasibility for real-world wastewater treatment applications.

This research makes a valuable contribution to the field of wastewater treatment by introducing a cost-effective and environmentally sustainable solution for the removal of toxic heavy metals. The integration of graphene oxide with chitosan not only enhances the adsorption capacity but also offers improved stability, recyclability, and biocompatibility. The study presents a novel approach to composite material design by combining the properties of graphene oxide and chitosan, offering a dual advantage of high surface area and functional groups from GO, along with the biodegradability and eco-friendliness of chitosan. This contribution expands the scope of nanocomposite applications in environmental remediation and could guide future innovations in sustainable materials for pollution control.

Despite the promising results, several limitations need to be addressed in future studies. The long-term stability and reusability of the graphene oxide-chitosan nanocomposite in real-world wastewater environments require further investigation. The effects of varying concentrations of metal ions and the presence of other contaminants in industrial effluents should also be studied to better simulate actual wastewater conditions. Future research could focus on optimizing the synthesis of the nanocomposite for larger-scale applications and evaluating its environmental impact, including potential toxicity and biodegradability in aquatic systems. Furthermore, the scalability of this composite for industrial use and its integration with existing wastewater treatment technologies could enhance its practical application.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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