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Development of a Peanut Shell-Derived Chitosan–Activated Carbon Composite as a Sustainable Adsorbent for Permanganate (MnO_4^-) Removal from Aqueous Solution

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Abstract
The presence of permanganate (MnO_4^-) in aqueous environments is an emerging environmental concern, as elevated concentrations may compromise aquatic ecosystems and water quality. Converting agricultural biomass into adsorbent materials offers a promising and sustainable route for addressing this issue. This study introduces a novel glutaraldehyde-crosslinked chitosan–activated carbon composite synthesized from peanut shell waste for removing permanganate ions under acidic conditions. Peanut shell biomass was first carbonized and then chemically activated with phosphoric acid to obtain activated carbon, which was subsequently blended with a chitosan solution through ionic gelation and stabilized by glutaraldehyde crosslinking. Functional group changes in the resulting composite were characterized by Fourier Transform Infrared (FTIR) spectroscopy, while its permanganate-removal performance was assessed through batch adsorption trials at pH 3, with residual concentrations measured spectrophotometrically using a calibration curve exhibiting excellent linearity ($R^2 = 0.996$). The FTIR spectra displayed noticeable shifts in absorption bands, confirming interaction between the functional groups of chitosan and activated carbon. Removal efficiencies of 93.48% and 91.60% were obtained for initial permanganate concentrations of 25 and 30 mg L^{-1}, equivalent to adsorption capacities of 5.84 and 6.87 mg g^{-1}, reflecting the synergistic role of the porous carbon framework and the amino/hydroxyl groups of chitosan as active binding sites. These findings confirm that peanut shell waste can be valorized into an effective, low-cost, and environmentally friendly adsorbent for permanganate remediation in water treatment.

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INTRODUCTION

The contamination of aquatic environments by heavy metals and their related compounds has become an increasingly important environmental issue as industrial activities continue to expand worldwide. Wastewater generated from mining operations, metal processing, electroplating, fertilizer production, battery manufacturing, and various chemical industries often contains metal-derived pollutants that may accumulate in natural water bodies if discharged without adequate treatment (Ali, 2018; Crini et al., 2019; Singh et al., 2024).

Among permanganate-containing chemicals, potassium permanganate ($KMnO_4$) is extensively employed as a powerful oxidizing agent in water purification, industrial processing, and laboratory applications because of its high oxidation capacity. However, improper dosing or incomplete consumption during oxidation processes may leave residual permanganate ions (MnO_4^-) in treated water, potentially affecting water quality and subsequent treatment efficiency. In addition, the strong oxidative nature of permanganate may influence aquatic eco-

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systems and pose toxicological risks when present at excessive concentrations (Martinez-Finley et al., 2022; Peres et al., 2020). Consequently, the development of efficient and environmentally sustainable methods for removing residual permanganate from aqueous systems has become an important research priority in the field of water treatment (Singh et al., 2024).

A variety of technologies have been developed to reduce heavy metal concentrations in wastewater, including membrane separation, ion exchange, chemical precipitation, electrochemical treatment, and adsorption (Ali, 2018; Crini & Lichtfouse, 2019). Among these approaches, adsorption has emerged as one of the most promising methods because of its operational simplicity, economic feasibility, and high removal efficiency (Ahmed et al., 2016; Biswal & Balasubramanian, 2023; Sembiring, 2025). Activated carbon derived from biomass resources has received considerable attention as an adsorbent material due to its well-developed porous structure and strong affinity toward various contaminants (Bayode et al., 2023; Guo et al., 2023; Wang et al., 2023). The utilization of agricultural residues for activated carbon production not only reduces waste generation but also supports the development of sustainable water treatment technologies (Biswal & Balasubramanian, 2023). Among the available agricultural by-products, peanut shells represent a promising precursor because of their high cellulose and lignin content (Patri, 2019; Wang et al., 2023).

Chitosan has been extensively investigated as a sustainable biopolymer for wastewater treatment because of its favorable physicochemical characteristics and strong affinity for metal ions. Produced through the deacetylation of chitin, this natural polymer contains a high density of amino (–NH_2) and hydroxyl (–OH) functional groups that serve as active binding sites for dissolved metal species via coordination, chelation, and ion-exchange mechanisms (Choi et al., 2024; Kumari et al., 2017; Narudin et al., 2021; Ranjan et al., 2024).

These characteristics make chitosan an environmentally benign adsorbent with broad potential for heavy metal remediation. Nevertheless, the direct application of pristine chitosan is hindered by several drawbacks, including inadequate mechanical strength, poor resistance under acidic conditions, and a relatively low specific surface area, all of which may limit adsorption efficiency and operational durability (Ghorai et al., 2021; Omer et al., 2022). To address these shortcomings, numerous modification strategies have been explored, particularly chemical crosslinking and the incorporation of porous supporting materials, with the aim of improving the structural stability and adsorption performance of chitosan-based adsorbents.

To overcome the inherent limitations of pristine chitosan, considerable research has focused on the development of composite adsorbents by integrating chitosan with porous carbonaceous materials. Among these materials, activated carbon derived from agricultural biomass has attracted widespread interest because of its renewable origin, low production cost, high carbon content, and well-developed porous structure, which collectively contribute to a large specific surface area and abundant adsorption sites (Wang et al., 2023).

Peanut shell waste represents a promising biomass precursor owing to its high lignocellulosic composition and wide availability, making it suitable for the production of sustainable activated carbon (Patri, 2019). When incorporated into a chitosan matrix, activated carbon not only enhances the porosity and mechanical stability of the composite but also provides additional active sites for contaminant adsorption, while chitosan contributes amino (–NH_2) and hydroxyl (–OH) functional groups that facilitate surface interactions. Furthermore, chemical crosslinking using glutaraldehyde has been widely adopted to reinforce the structural integrity, chemical resistance, and reusability of chitosan-based composites, thereby improving their applicability in aqueous treatment systems (Gamage et al., 2023; Lansari et al., 2025).

Previous studies have reported the successful application of biomass-derived activated carbon and modified chitosan for the removal of heavy-metal cations, dyes, and other aqueous contaminants. Activated carbon prepared from various agricultural residues has demonstrated high adsorption capacity owing to its porous structure and large specific surface area, while chemically modified chitosan has been widely investigated because of its abundant amino and hydroxyl functional groups that facilitate contaminant binding (Sheraz et al., 2024; Wang et

al., 2023). In addition, glutaraldehyde has frequently been employed as a crosslinking agent to improve the structural stability and chemical resistance of chitosan-based adsorbents (Lansari et al., 2025; Rostami & Khodaei, 2024). More recently, Nandamol and Porel (2025) developed a guanidinium-based ionic porous organic polymer for the efficient adsorption of permanganate ions (MnO_4^-), demonstrating that tailored functional materials can effectively remove residual permanganate from water. Nevertheless, their study employed a synthetic porous polymer rather than a renewable biomass-derived composite.

Bio-based materials have likewise been reviewed as viable alternatives for permanganate remediation (Moyo et al., 2020), and chitosan itself has been reported to influence permanganate immobilization through biopolymer-mediated mechanisms (Zhang et al., 2024), yet its combination with biomass-derived activated carbon for this purpose remains largely unexplored. Likewise, previous investigations on peanut shell-derived activated carbon and chitosan have mainly focused on heavy-metal cations or organic pollutants instead of permanganate ions (Sheraz et al., 2024; Tsauria et al., 2025; Wang et al., 2023). Therefore, studies concerning glutaraldehyde-crosslinked chitosan–activated carbon composites prepared from peanut shell waste for permanganate adsorption remain very limited, particularly those examining the relationship between composite functional groups and adsorption behavior under acidic conditions.

Based on the identified research gap, this study proposes the development of a glutaraldehyde-crosslinked chitosan–activated carbon composite derived from peanut shell waste as a sustainable adsorbent for the removal of permanganate ions (MnO_4^-) from aqueous solutions. Unlike previous studies, which generally investigated activated carbon and chitosan as separate adsorbent materials or employed synthetic polymers for permanganate adsorption, the present work integrates peanut shell-derived activated carbon, chitosan, and glutaraldehyde crosslinking into a single biomass-based composite (Nandamol & Porel, 2025; Patri, 2019; Wang et al., 2023).

This approach is expected to enhance the structural stability, increase the availability of adsorption sites, and improve the interaction between the composite surface and permanganate ions under acidic conditions. The synthesized composite was characterized using Fourier Transform Infrared (FTIR) spectroscopy to identify the functional groups involved in composite formation and adsorption, while the adsorption performance was evaluated by UV–Visible spectrophotometry through monitoring the residual permanganate concentration. The findings are expected to expand current knowledge regarding sustainable biomass-based composite adsorbents and promote the value-added utilization of peanut shell waste for environmentally friendly water treatment applications. The proposed composite may also provide an alternative strategy for converting agricultural waste into value-added adsorbent materials, thereby supporting sustainable environmental remediation and circular resource utilization (Biswal & Balasubramanian, 2023; Guo et al., 2023).

METHOD

This research adopted a laboratory-based experimental design to prepare a chitosan–activated carbon composite from peanut shell biomass and to examine its ability to remove permanganate ions (MnO_4^-) from aqueous media. The study was carried out through four sequential stages. Initially, activated carbon was produced from peanut shells by carbonization followed by chemical activation using phosphoric acid, with slight modifications to previously reported procedures (Wang et al., 2023). Subsequently, the activated carbon was combined with a chitosan solution and chemically crosslinked using glutaraldehyde to obtain a stable composite adsorbent (Hsu et al., 2024).

The synthesized material was then characterized using Fourier Transform Infrared (FTIR) spectroscopy to identify the functional groups involved in composite formation and the potential adsorption sites (Ghorai et al., 2021). The adsorption performance of the composite was evaluated using a batch adsorption method with potassium permanganate ($KMnO_4$) solution as the model contaminant. Adsorption experiments were conducted under controlled acidic conditions (pH 3), and the remaining permanganate concentration after treatment was determined by UV–Visible spectrophotometry

following established analytical procedures (Ali, 2018; Singh et al., 2024).

The present investigation was designed as a preliminary assessment of the adsorption capability of the synthesized composite. Therefore, the experimental variables were limited to a fixed solution pH of 3 and two representative initial permanganate concentrations of 25 and 30 mg L^{-1}. These operating conditions were selected to provide an initial evaluation of the composite performance before conducting more comprehensive studies involving wider pH ranges, concentration variations, adsorption kinetics, and equilibrium analyses.

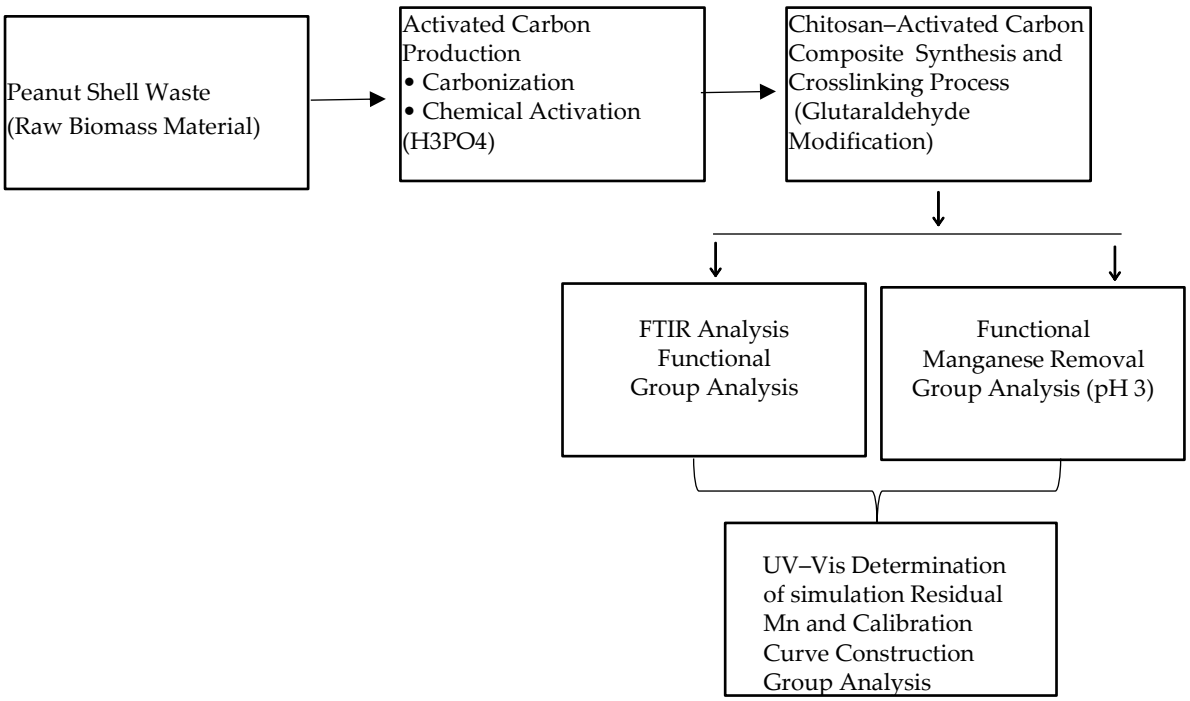


Figure 1. Research Flow Diagram of Activated Carbon Preparation, Composite Synthesis, Characterization, and Permanganate Adsorption Experiment

Materials and Instruments

The materials used in this study included chitosan, peanut shell waste as the precursor for activated carbon production, phosphoric acid (H_3PO_4), glutaraldehyde, acetic acid (CH_3COOH), sodium hydroxide (NaOH), ethanol, distilled water, and potassium permanganate ($KMnO_4$), which served as the source of permanganate ions (MnO_4^-) in the adsorption experiments. Unless otherwise stated, all chemicals were of analytical grade and were used without further purification. The experimental work was carried out using a furnace for carbonization, drying oven, analytical balance, a magnetic stirrer, a mechanical shaker, a pH meter, a Fourier Transform Infrared (FTIR) spectrophotometer for functional group characterization, and a UV–Visible spectrophotometer for determining the residual permanganate concentration after adsorption.

Synthesis of Chitosan–Activated Carbon Composite

Peanut shell waste was used as the raw material for activated carbon production. The biomass was first carbonized at 400 °C for 60 min and subsequently activated by immersion in a 15% phosphoric acid (H_3PO_4) solution to improve pore development and surface functionality, following a modified biomass activation procedure reported by Wang et al. (2023).

After chemical activation, the carbon was repeatedly washed with distilled water until a neutral pH was attained and then dried in an oven at 110 °C to remove residual moisture. For composite preparation, 1 g of chitosan was dissolved in 40 mL of 2% (v/v) acetic acid (CH_3COOH) under continuous stirring until a homogeneous polymer solution was obtained, following the dissolution procedure described by Kumari et al. (2017), consistent with comparable chitosan preparation protocols reported for biomass-derived chitosan (Mahatmanti et al., 2022). Activated carbon was then added to the chitosan solution at a mass ratio of 1:1 (w/w), and the mixture was stirred continuously to ensure uniform dispersion of the carbon particles within the polymer matrix (Ghorai et al., 2021).

The resulting suspension was added dropwise into 0.1 M sodium hydroxide (NaOH) solution to

produce composite beads through ionic gelation. The beads were subsequently immersed in a 5.5% glutaraldehyde solution for 24 h to chemically crosslink the chitosan matrix and improve its mechanical strength and chemical stability, following the approach reported for crosslinked chitosan adsorbents (El Messaoudi & Mohammed, 2024; Omer et al., 2022). After crosslinking, the beads were thoroughly washed with distilled water until neutral pH was achieved to remove excess reagents and unreacted glutaraldehyde. Finally, the composite beads were dried at 60 °C to constant weight before being subjected to Fourier Transform Infrared (FTIR) characterization and batch adsorption experiments using potassium permanganate ($KMnO_4$) solution.

Characterization of Adsorbent

The functional groups of activated carbon, chitosan, and the synthesized chitosan–activated carbon composite were characterized using Fourier Transform Infrared (FTIR) spectroscopy. FTIR analysis was performed to identify the characteristic chemical bonds of each material and to verify the successful formation of the composite, following the general characterization approach reported by (Ghorai et al., 2021; Haider et al., 2024). The spectra were recorded over the wavenumber range of 4000–400 cm^{-1}, which is commonly employed for identifying the major functional groups present in carbonaceous and chitosan-based adsorbents (Federer et al., 2021).

The obtained spectra were interpreted by comparing the characteristic absorption bands of activated carbon, chitosan, and the composite material. Peak positions, absorption intensities, and spectral shifts were analyzed to identify the presence of hydroxyl (–OH), amino ($–NH_2$), carbonyl (C=O), and C–O functional groups and to evaluate the interactions occurring between activated carbon and the chitosan matrix during composite formation (Ghorai et al., 2021; Ranjan et al., 2024). Changes in these spectral features were used as evidence of successful composite synthesis and the incorporation of activated carbon into the crosslinked chitosan network.

Determination of Permanganate Concentration and Adsorption Efficiency

A calibration curve was established using potassium permanganate ($KMnO_4$) standard solutions with concentrations of 5, 10, 15, 20, 25, and 30 mg L^{-1}. The absorbance of each standard solution was measured at the maximum absorption wavelength using a UV–Visible spectrophotometer, following the Beer–Lambert principle for quantitative analysis (Ali, 2018; Wang et al., 2023). A linear regression equation describing the relationship between absorbance and permanganate concentration was subsequently generated and used to determine the residual permanganate concentration after the adsorption process (Singh et al., 2024).

The adsorption performance of the synthesized chitosan–activated carbon composite was evaluated using a batch adsorption technique under controlled acidic conditions (pH 3), adapted from commonly reported adsorption procedures for aqueous contaminants (Ali, 2018; Crini et al., 2019). Two representative initial permanganate concentrations, namely 25 and 30 mg L^{-1}, were selected for this preliminary investigation. In each experiment, 0.1 g of the composite adsorbent was mixed with 25 mL of $KMnO_4$ solution and agitated at 200 rpm for 90 min at room temperature to ensure sufficient contact between the adsorbent and the solution (Omer et al., 2022; Singh et al., 2024). The concentration values were determined from the previously established calibration equation.

The percentage of permanganate removal was calculated according to Equation (1):

$$\eta = \frac{C_o - C_e}{C_o} \times 100$$

where η denotes the adsorption efficiency (%), C_0 represents the initial permanganate concentration (mg L^{-1}), and C_e corresponds to the permanganate concentration at equilibrium (mg L^{-1}). The obtained efficiency values were used to evaluate the adsorption performance of the prepared chitosan–activated carbon composite for permanganate removal from aqueous solutions.

Adsorption Capacity

To complement the removal efficiency analysis, the adsorption capacity of the synthesized composite was also calculated using Equation (2):

$$q_e = ((C_0 - C_e) \times V) / m$$

where: q_e = adsorption capacity (mg g^{-1}); C_0 = initial permanganate concentration (mg L^{-1}); C_e = equilibrium permanganate concentration (mg L^{-1}); V = solution volume (L); and m = adsorbent mass (g).

Although the primary performance indicator discussed in this study is removal efficiency, the adsorption capacity was additionally calculated to provide a quantitative description of the amount of permanganate adsorbed per unit mass of adsorbent. Reporting both parameters allows a more comprehensive evaluation of the adsorption performance and facilitates comparison with previous adsorption studies.

RESULTS AND DISCUSSION

Synthesis of Crosslinked Chitosan–Activated Carbon Composite from Peanut Shell Biomass

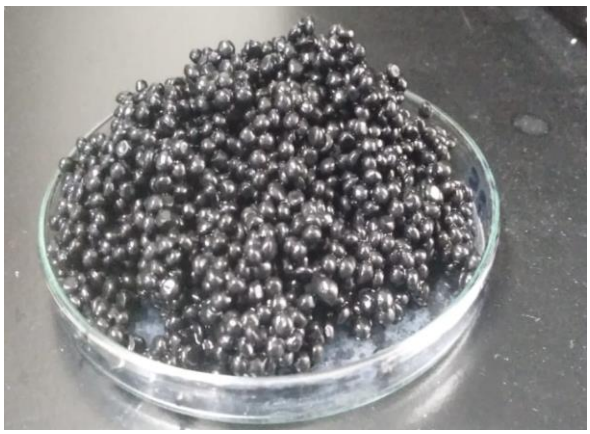


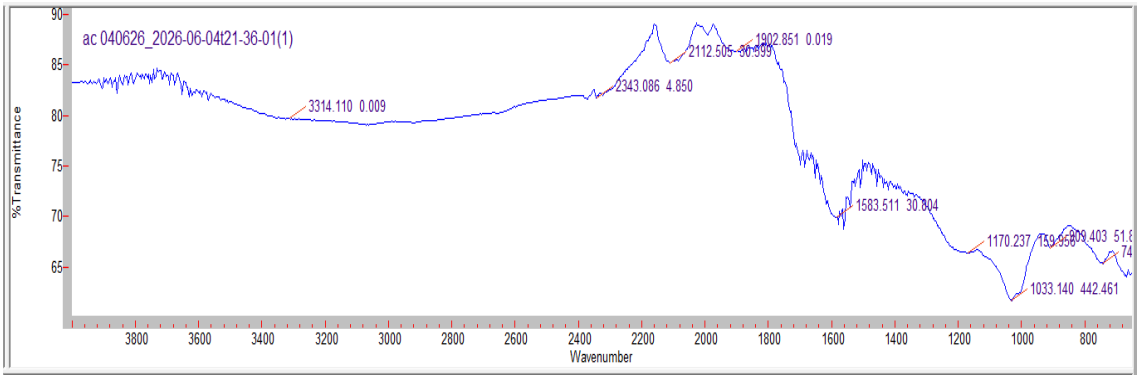
Figure 2. Composite Adsorbent Based on Chitosan and Activated Carbon Prepared from Peanut Shell Biomass.

The chitosan–activated carbon composite synthesized from peanut shell waste is presented in Figure 2. The prepared material appeared as a black solid with a fairly uniform morphology, indicating that the activated carbon was well distributed throughout the chitosan matrix. The composite was produced by integrating activated carbon derived from peanut shells into a chitosan solution, where chitosan functioned as a supporting matrix and binding agent to form a stable adsorbent structure.

In addition to enhancing the structural integrity of the material, chitosan provides amino ($–NH_2$) and hydroxyl (–OH) groups that play an important role as active adsorption sites. No visible separation between the activated carbon and chitosan phases was observed, suggesting effective interaction and successful formation of the composite material. The combination of the porous characteristics of activated carbon and the functional groups of chitosan is expected to improve the adsorption behavior of the composite, making it a promising material for the removal of contaminants from aqueous media.

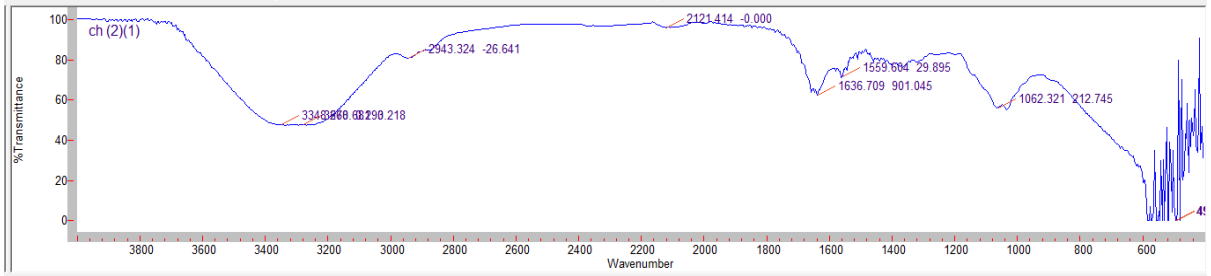
4.2. FTIR Characterization of Peanut Shell-Derived Chitosan–Activated Carbon Composite

The FTIR spectra of activated carbon, chitosan, and the chitosan–activated carbon composite with a 1:1 composition are shown in Figures 3–5. Comparative analysis of the spectra revealed several changes in the characteristic absorption bands after composite formation, indicating the successful integration of chitosan into the activated carbon structure. The broad band initially observed at 3314 cm^{-1} in activated carbon shifted to 3259 cm^{-1} in the composite. This shift is associated with the interaction of hydroxyl and amino groups from chitosan with oxygen-containing functional groups present on the activated carbon surface, leading to the formation of intermolecular hydrogen bonds.



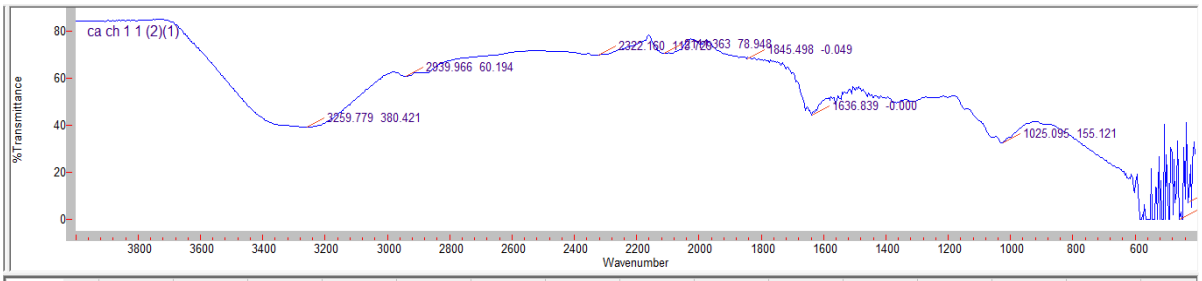
Peak List	Center	Area	Height	Left Edge	Right Edge
Peak1	745.122	-90.248	1.770	798.777	731.669
Peak2	909.403	-51.870	1.717	921.809	878.934
Peak3	1033.140	-442.461	5.845	1085.852	984.257
Peak4	1170.237	-159.956	1.169	1252.691	1154.825
Peak5	1583.511	-30.804	0.081	1616.196	1582.641
Peak6	1902.851	-0.019	0.010	1903.271	1901.407
Peak7	2112.505	-30.599	0.944	2135.354	2106.460
Peak8	2343.086	-4.850	0.668	2345.068	2333.883
Peak9	3314.110	-0.009	0.009	3316.277	3314.413

Figure 3. Fourier Transform Infrared (FTIR) Spectrum of Activated Carbon Derived from Peanut Shell Waste.



Peak List	Center	Area	Height	Left Edge	Right Edge
Peak1	491.197	8.854	-24.604	497.721	495.857
Peak2	493.061	0.000	53.790	486.536	486.536
Peak3	1062.321	-212.745	4.235	1123.135	1054.162
Peak4	1559.604	-29.895	4.885	1567.728	1554.679
Peak5	1636.709	-901.045	18.292	1676.780	1611.535
Peak6	2121.414	0.000	0.088	2115.781	2115.781
Peak7	2943.324	26.641	3.594	2963.025	2748.651
Peak8	3278.681	-0.218	0.056	3280.858	3275.266
Peak9	3348.560	-0.293	0.113	3351.695	3347.967

Figure 4. FTIR Spectrum Showing the Characteristic Functional Groups of Chitosan



Peak List	Center	Area	Height	Left Edge	Right Edge
Peak1	426.785	0.000	16.020	421.292	421.292
Peak2	455.778	0.000	5.475	451.118	451.118
Peak3	1025.095	-155.121	3.826	1035.521	970.277
Peak4	1636.839	0.000	1.511	1632.973	1632.973
Peak5	1845.498	0.049	0.206	1864.124	1862.260
Peak6	2111.363	-78.948	2.186	2133.490	2101.800
Peak7	2322.160	-113.729	0.568	2326.427	2241.609
Peak8	2939.966	-60.194	1.701	2959.297	2915.490
Peak9	3259.779	-380.421	0.208	3262.217	3120.544

Figure 5. FTIR Spectrum Showing the Characteristic Functional Group of Chitosan–Activated Carbon Composite (1:1)

An additional absorption band appeared at 2939 cm^{-1} in the composite spectrum, which is attributed to aliphatic C–H stretching vibrations originating from the chitosan polymer chain. Changes were also observed in the absorption region between 2121 and 2343 cm^{-1}, where the band position shifted to 2322 cm^{-1} following composite synthesis. This region is generally related to adsorbed carbon dioxide or carbon-containing species and is not considered a major indicator of composite formation. Moreover, the absorption peak located at 1903 cm^{-1} in activated carbon moved to 1845 cm^{-1} in the composite, suggesting modifications in the local chemical environment caused by interactions between the constituent. A significant spectral change was detected in the region around 1600 cm^{-1}.

The band originally appearing at 1583 cm^{-1} shifted to 1636 cm^{-1} after the incorporation of chitosan. This absorption is commonly associated with N–H bending vibrations and may also reflect the contribution of amide-related functional groups present in chitosan. In addition, the peak at 1033 cm^{-1} was displaced to 1025 cm^{-1} in the composite spectrum, corresponding to C–O and C–O–C stretching vibrations characteristic of the chitosan structure. The observed peak shifts and the emergence of new absorption bands provide evidence of intermolecular interactions between chitosan and activated carbon, confirming the successful formation of the chitosan–activated carbon composit

Adsorption Performance of Potassium Permanganate Using a Chitosan–Activated Carbon Composite Derived from Peanut Shells.

A distinct visual change was observed in the potassium permanganate solution before and after the adsorption experiment, as illustrated in Figure 6. Prior to treatment with the adsorbent (Figure 6a), the solution displayed a dark purple

color, reflecting the relatively high concentration of permanganate ions present in the aqueous phase. After the adsorption process had been completed (Figure 6b), the intensity of the purple coloration decreased substantially, resulting in a noticeably clearer solution.



(a) (b)

Figure 6. (a) Potassium Permanganate Solution before Adsorption and (b) Potassium Permanganate Solution after Adsorption.

In addition, the chitosan–activated carbon composite was found to accumulate at the bottom of the container, indicating successful contact between the adsorbent and the dissolved species during the adsorption process. The observed reduction in color intensity suggests that a portion of the permanganate ions was removed from the solution and retained by the adsorbent material. This visual evidence qualitatively demonstrates the adsorption capability of the synthesized composite toward dissolved contaminants. The gradual fading of the characteristic purple color indicates a decrease in the concentration of potassium permanganate remaining in the solution after treatment. Such adsorption behavior is likely related to the synergistic contribution of activated carbon and chitosan, where the porous structure of activated carbon provides a large surface area for adsorption, while the amino and hydroxyl functional groups of chitosan facilitate interactions with ionic species through various physicochemical mechanisms. These findings provide preliminary evidence of the effectiveness of the prepared composite as an adsorbent material for aqueous pollutant removal.

Overall, the visual results demonstrate the promising adsorption capability of the peanut shell-derived chitosan–activated carbon composite. The substantial decrease in color intensity after treatment suggests that the material has potential for application in water purification and wastewater remediation processes involving dissolved contaminants. This preliminary observation is further supported by quantitative analyses presented in the subsequent sections.

Calibration Curve Analysis and Adsorption Capacity of a Chitosan–Activated Carbon Composite for Permanganate Ion Removal

Table 1. permanganate standard solutions

No	Concentration (PPM)	Absorbance
1	5	0.268
2	10	0.467
3	15	0.649
4	20	0.928
5	25	1.121
6	30	1.389

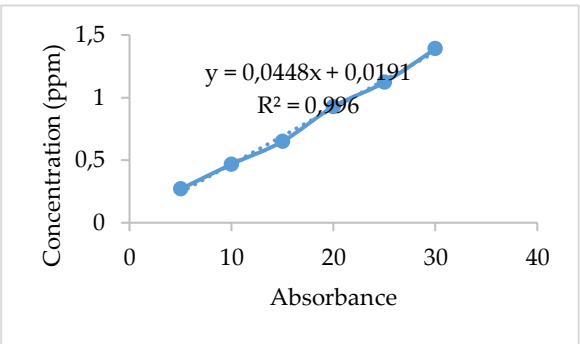


Figure 7. Calibration Curve of Permanganate Standard Solutions

The concentration of permanganate remaining in solution after the adsorption process was

quantified using UV–Visible spectrophotometry based on a calibration curve constructed from permanganate standard solutions with concentrations ranging from 5 to 30 ppm. An increase in absorbance was observed with increasing permanganate concentration, demonstrating a direct linear relationship consistent with the Beer–Lambert principle. Regression analysis of the calibration data generated the equation $y = 0.0448x + 0.0191$ with a coefficient of determination (R^2) of 0.996. This result indicates excellent linearity and confirms the reliability of the calibration model for the quantitative analysis of permanganate ions in aqueous solutions.

Table 2. Permanganate Standard Solutions

Sample	Absorbance	Final Concentration (ppm)	Removal efficiency (%)	Adsorption Capacity (mg g^{-1})
25 ppm	0.092	1.63	93.48	5.84
30 ppm	0.132	2.52	91.60	6.87

The calibration equation was subsequently applied to determine the residual permanganate concentration following adsorption. The results showed that the initial permanganate concentrations of 25 ppm and 30 ppm decreased to 1.63 ppm and 2.52 ppm, respectively. The considerable decline in permanganate concentration demonstrates the strong adsorption capability of the synthesized chitosan–activated carbon composite. Such performance is likely associated with the availability of active functional groups originating from both chitosan and activated carbon, which promote the interaction and retention of permanganate ions on the adsorbent surface.

The effectiveness of the adsorption process was further assessed through the calculation of permanganate removal efficiency. As summarized in Table 2, the composite achieved removal efficiencies of 93.48% and 91.60% for initial permanganate concentrations of 25 ppm and 30 ppm. In addition, the corresponding adsorption capacities were 5.84 and 6.87 mg g^{-1} respectively. These findings indicate that the adsorbent maintained a high level of performance even when exposed to higher metal concentrations. The slight reduction in removal efficiency at 30 mg L^{-1} is likely associated with the gradual saturation of available adsorption sites, which limits the number of additional permanganate ions that can be accommodated on the adsorbent surface. Similar trends have frequently been reported in adsorption studies where the adsorption capacity becomes constrained by the finite number of active binding sites (Ranjan et al., 2024; Sheraz et al., 2024; Wang et al., 2023).

The high removal efficiency obtained in this work demonstrates the complementary functions of chitosan and activated carbon within the composite structure. Chitosan contributes amino and hydroxyl groups that serve as active binding sites for metal ions, whereas activated carbon provides a porous framework and extensive surface area that facilitate the adsorption process. The combination of these properties results in enhanced adsorption performance compared with the individual components. Overall, the results indicate that the chitosan–activated carbon composite prepared from peanut shell waste is a highly promising adsorbent for permanganate removal from aqueous systems. The ability to achieve removal efficiencies exceeding 90% highlights its potential for application in environmentally sustainable water treatment processes, particularly as a low-cost adsorbent derived from renewable agricultural waste resources.

CONCLUSION

A glutaraldehyde-crosslinked chitosan–activated carbon composite was successfully synthesized from peanut shell waste and evaluated as an adsorbent for permanganate ions (MnO_4^-) in aqueous solution. The composite achieved removal efficiencies of 93.48% and 91.60% at initial permanganate concentrations of 25 and 30 mg L^{-1}, respectively. FTIR analysis confirmed the successful incorporation of activated carbon into the chitosan matrix through the presence of characteristic functional groups associated with the composite structure. The novelty of this study lies in the utilization of peanut shell waste as a precursor for preparing a glutaraldehyde-crosslinked chitosan–activated carbon composite and demonstrating its applicability for permanganate ion removal under acidic conditions. The combination of activated carbon and chitosan provides a porous adsorption medium enriched with oxygen- and

nitrogen-containing functional groups, which are expected to facilitate the adsorption process. The results indicate that peanut shell waste has potential as a renewable raw material for producing value-added adsorbents for water treatment applications. This study contributes to the development of sustainable biomass-based adsorbent materials and provides a foundation for future investigations involving adsorption kinetics, equilibrium isotherms, regeneration, reusability, and performance evaluation under a wider range of operating conditions before practical implementation.

RECOMMENDATION

Further research should focus on optimizing adsorption operating conditions and evaluating adsorption isotherm and kinetic models to better elucidate the adsorption mechanism. The performance of the composite should also be validated using real wastewater containing permanganate and other metal contaminants. In addition, increasing the number of experimental replicates and expanding the range of operating conditions would improve the robustness and reliability of the findings.

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