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BIOPOLYMER-BASED ADSORPTION OF CONGO RED USING MODIFIED K-CARRAGEENAN: TOWARDS SAFER WATER AND ENVIRONMENTAL HEALTH PROTECTION

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Abstract

Introduction: *The discharge of synthetic dyes such as Congo Red (CR) into water systems poses serious threats to aquatic biodiversity, deteriorates water quality, and raises public health risks due to their toxicity, persistence, and tendency to bioaccumulate. This study investigates the potential of chemically modified κ-carrageenan as a biosorbent for CR removal under varying conditions.* ***Methods:*** *Two forms of κ-carrageenan were prepared: unmodified (κC) and modified (mκC). Functional groups were identified using Fourier Transform Infrared Spectroscopy (FTIR), while surface morphology was examined via Scanning Electron Microscopy (SEM). Batch adsorption experiments were conducted to assess how dye concentration, contact time, and adsorbent amount affect Congo Red removal, measured by UV-Vis spectrophotometry and analyzed using Langmuir and Temkin isotherm models.* ***Results and Discussion:*** *The mκC achieved 93.3% removal efficiency at an initial CR concentration of 20 mg/L, reaching equilibrium within 60 minutes at an optimal dosage of 0.3 g. FTIR confirmed the presence of functional groups such as carbonyl, sulfonate, and amide. SEM revealed an increase in the biosorbent's roughness and porosity. Isotherm modelling showed a strong fit to the Langmuir model, with an R^2 value of 0.9974 and a maximum adsorption capacity of 476.19 mg/g. The Temkin model also revealed a good correlation (R^2=0.9511), indicating that chemisorption is the primary mechanism of adsorption.* ***Conclusion:*** *Modified κ-carrageenan is a cost-effective and biodegradable biosorbent for dye removal, with potential for wastewater treatment. Future research on regeneration and real-world applications will enhance its role in improving water quality and protecting environmental health.*

INTRODUCTION

Many industries, including textiles, paper, leather, and cosmetics, use synthetic dyes a lot. Azo dyes like Congo Red (CR) are especially common. They are popular because they come in bright colors, are very stable chemically, and are cheap. But the widespread use and improper disposal of these dyes have caused major pollution problems, especially in our water ecosystems (1). It is thought that 7,107 tons of synthetic dyes are made every year around the world, which shows how widely they are used in industry. The textile industry alone uses more than 10,000 tons of water each year, and a lot of it ends up in wastewater during dyeing and finishing. Synthetic dyes can be detected even at trace levels and, unlike many conventional pollutants such as heavy metals or pesticides, they are highly resistant to natural degradation in aquatic environments. Their persistence enables them to disrupt ecosystems by limiting light penetration and thereby inhibiting photosynthesis. Owing to these properties, dyes are considered one of the most difficult classes of pollutants to manage. Their ecological persistence and toxic effects underscore the urgent need for effective and sustainable treatment approaches (2).

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Among these pollutants, Congo Red (CR) stands out as an anionic, water-soluble dye belonging to the benzidine-based azo group. CR is particularly concerning because of its cytotoxic, mutagenic, and potentially carcinogenic properties. Even at very low concentrations, it imparts a vivid coloration to water, disrupts photosynthetic activity in aquatic plants, and resists natural breakdown, allowing it to persist in the environment for extended periods (3). The presence of dyes in wastewater presents serious ecological and public health concerns, emphasizing the urgent need for effective treatment methods. Traditional approaches to dye removal, such as coagulation-flocculation, membrane filtration, and chemical oxidation, often come with high operational costs, produce sludge, and have limited efficiency in treating dilute solutions. Adsorption has really become a go-to method for many because it's straightforward, budget-friendly, highly effective at removing impurities, and offers great flexibility in how it can be applied. It's no wonder it's gaining so much traction (4-5). The choice of adsorbent materials is critical to the success in this method.

In the future, the cost of goods and raw materials is projected to increase steadily, which has intensified the search for cost-effective and sustainable alternatives to conventional adsorbents. Numerous studies have reported the use of inexpensive materials such as graphene oxide, bentonite, chitosan-crosslinked κ-carrageenan, magnetic graphene combined with calcium alginate, magnetic carboxymethyl starch, and pineapple peel cellulose for the removal of methylene blue dye. Several of these adsorbents have shown adsorption capacities that approach or even rival those of activated carbon, although others still exhibit relatively modest performance (6). Lately, there has been growing interest in using natural biopolymers as sustainable adsorbents. They stand out because they're readily available, biodegradable, and have functional groups that really help in binding pollutants. This makes them a great option for environmentally friendly applications (7).

κ-Carrageenan is a naturally occurring polysaccharide derived from red seaweed of the Rhodophyceae family. Its backbone is composed of alternating units of D-galactose and 3,6-anhydro-D-galactose. A key characteristic of κ-carrageenan is the presence of hydroxyl and sulfate groups, which act as functional sites capable of interacting with other molecules through ion exchange, hydrogen bonding, and electrostatic attraction (8). Because of these versatile interactions, κ-carrageenan is widely used across diverse sectors, including food, pharmaceuticals, and cosmetics (9). Despite these advantages, its native form is limited by high moisture affinity and relatively low mechanical strength, both of which can reduce adsorption efficiency. To address these shortcomings, researchers commonly apply chemical modifications using crosslinking agents such as glutaraldehyde or N,N′-methylenebisacrylamide (MBA). These treatments enhance the structural stability of the material, improve porosity, and increase reusability, making κ-carrageenan more effective for adsorption-based applications (10-11).

Although advancements have been made, few detailed investigations have focused on how different crosslinkers influence κ-carrageenan's adsorption efficiency, particularly for dye removal (12). Understanding how structural, chemical, and elemental modifications affect adsorption under various environmental conditions is therefore essential. Such insights can inform the design of improved materials and ultimately strengthen their performance in real-world applications (13). To address the challenge of removing Congo Red (CR) dye from aqueous solutions, this study focuses on the development and application of modified κ-carrageenan hydrogel beads. The main objective of this work was to improve the adsorption capacity of κ-carrageenan through chemical crosslinking and to assess how different environmental factors affect the adsorption process. To characterize the modified materials, Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were utilized. These techniques provided detailed insights into structural alterations and verified the successful incorporation of new functional groups.

Batch adsorption experiments were carried out to evaluate the influence of three key parameters—initial dye concentration, contact time, and adsorbent dosage—on the removal efficiency of Congo Red (CR). To further interpret the adsorption process, isotherm models were applied, providing valuable insights into the interactions between CR molecules and the adsorbent surface. These findings help to clarify the mechanisms governing the adsorption behavior. Beyond the laboratory scale, this work contributes to the advancement of cost-effective, biodegradable, and environmentally sustainable materials for wastewater treatment, an urgent need given the rising concern over water pollution and synthetic dye contamination worldwide. By emphasizing sustainable remediation strategies, the study aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-Being) and SDG 6 (Clean Water and Sanitation). Ultimately, the use of renewable, marine-derived biopolymers such as κ-carrageenan offers a promising pathway for protecting the environment while reducing risks to human health.

METHODS

This study focused on two types of κ-carrageenan adsorbents: unmodified (uκC) and modified (mκC). Batch biosorption experiments were conducted under controlled laboratory conditions to evaluate their performance. The experiments assessed adsorption efficiency across a range of operational parameters, including initial dye concentrations (5, 10, 15, 20, and 25 mg/L), contact times (15–240 minutes), and adsorbent dosages (0.05, 0.1, 0.2, 0.3, and 0.5 g). All tests were carried out at a constant room temperature of approximately 35 °C.

For data analysis, IBM SPSS Statistics 26 was employed due to its robust statistical modeling features and widespread use in environmental engineering and adsorption research. Its curve-fitting and regression tools were particularly useful for isotherm modeling and comparative performance evaluation. The Langmuir and Temkin models were applied to interpret adsorption behavior, providing insights into the biosorption capacity and surface interactions of the κ-carrageenan adsorbents (14).

Chemicals

All reagents employed in this study were of analytical grade and obtained from Merck. Acrylic acid (AA) was used as the main monomer in the polymerization process, with ammonium persulfate (APS) serving as the initiator. Crosslinking was achieved using N,N′-methylenebisacrylamide (MBA) together with 12.5% glutaraldehyde, both of which played a key role in enhancing the structural stability of the synthesized material. While these crosslinkers are widely used for improving the stability and reusability of biopolymer-based adsorbents, their sustainability and environmental implications are acknowledged. Future work will consider greener alternatives and regeneration strategies to align with sustainable material development practices (15). To facilitate the hardening of the beads, potassium chloride (KCl) was incorporated into the process, and Congo red dye was employed for the adsorption experiments. The pH levels of the solution were carefully adjusted with 1M sodium hydroxide (NaOH) and 1M hydrochloric acid (HCl). For the solvents, distilled water that was prepared in the laboratory were used.

Preparation of Biosorbents

Unmodified κ-carrageenan (uκC) beads were prepared by dissolving 2 g of κ-carrageenan in 90 mL of distilled water and heating the solution to 60 °C. The mixture was then cooled to 50–55 °C to facilitate gel formation. The gel was carefully dropped into 50 mL of 0.3 M KCl to produce spherical beads, which were allowed to harden for 1 h. After hardening, the beads were rinsed with distilled water followed by KCl solution, dried at room temperature, and stored in sealed containers for subsequent adsorption experiments.

For the preparation of modified κ-carrageenan (mκC) beads, the same procedure was initially followed, with 2 g of κ-carrageenan dissolved in 90 mL of distilled water, heated to 60 °C, and cooled to 50–55 °C. The solution was then introduced dropwise into a biphasic system containing palm olein oil and 0.3 M KCl, where the beads were allowed to harden for 1 h. The hardened beads were rinsed with distilled water and KCl solution, then air-dried at room temperature. To prepare the coating, the dried beads were immersed overnight in a solution containing 10 mL acrylic acid, 0.2 g MBA, 2 mL of 0.5% ammonium persulfate (APS), 5 mL of 12.5% glutaraldehyde, and 5 mL of 3 M KCl. Finally, the beads were rinsed thoroughly with distilled water and left to air dry at room temperature.

Characterization of Biosorbents

The structural properties of both coated and uncoated κ-carrageenan were analyzed using Fourier Transform Infrared (FTIR) spectroscopy. Spectra were recorded in the range of 600–4000 cm^{-1} with a Perkin Elmer Frontier instrument operating in attenuated total reflectance (ATR) mode. Surface morphology of the hydrogel beads was further examined using a FEI QUANTA scanning electron microscope (SEM), providing detailed insight into structural features and textural differences between the samples.

Batch Adsorption Study

A batch adsorption system was employed to evaluate the influence of key parameters on the removal of Congo Red (CR). Initial dye concentrations were varied at 5, 10, 15, 20, and 25 mg/L, with contact times ranging from 15 to 240 minutes, and adsorbent dosages set at 0.05, 0.1, 0.2, 0.3, and 0.5 g. The objective was to compare the adsorption performance of unmodified (uκC) and modified (mκC) κ-carrageenan composites. For a representative test, 0.2 g of either uκC or mκC was added to a 100 mL conical flask containing 25 mL of a 20 mg/L CR solution. The mixtures were then agitated at 30 °C using a magnetic stirrer to ensure proper mixing and contact between the adsorbent and dye molecules. The samples were carefully moved into falcon tubes for additional analysis following the treatment period.

A UV-Vis spectrophotometer set to 498 nm was used to measure the concentration of Congo Red

(CR) both before and after the adsorption process. We conducted blank experiments to guarantee the accuracy of the findings. To improve statistical analysis's reliability and reproducibility, each set of experimental conditions was carried out three times.

Adsorption Calculation and Isotherm Modelling

The removal percentage (%), was calculated using the following Eq. 1 (11).

$$\text{Removal Efficiency (\%)} = \frac{C_e - C_0}{C_0} \times 100 \quad (1)$$

where C_0 and C_e are the initial and equilibrium concentrations (mg/L)

Langmuir and Temkin isotherms were used in data analysis using IBM SPSS Statistics 26 to assess equilibrium behavior and adsorption capacity (10,16–18). Eqs. 2 and 3 represent the Langmuir and Temkin isotherms in their linear form. While the R_L and B_T for the two isotherms were calculated from Eq. 4, the Langmuir constant, KL, and Temkin constant, KT, were extracted from the linear plots using Eqs. 2 and 3, respectively.

$$\frac{1}{q_e} = \frac{1}{q_m K_L C_e} + \frac{1}{q_m}$$

$$q_e = \frac{RT}{B_T} \ln K_T + \frac{RT}{B_T} \ln C_e$$

$$R_L = \frac{1}{1 + C_0 K_L}$$

Where q_m denotes the maximum biosorbent's monolayer capacity for the adsorbate (mg/g).

Manuscript Assistance

The initial literature review and discussion sections were drafted with support from OpenAI's GPT-4 model. The authors utilised digital tools to enhance grammar and language clarity. All scientific content was independently prepared and validated by the authors.

RESULTS

The adsorption performance of two κ-carrageenan-based adsorbents, unmodified (uκC) and modified (mκC), was evaluated for the removal of Congo Red (CR) from aqueous solutions. The study focused on three main parameters: initial dye concentration, contact time, and adsorbent dosage. Removal efficiency was determined by comparing CR concentrations before and after treatment using a UV–Vis spectrophotometer, providing an accurate measure of adsorption capacity. Structural characterization offered additional insight. Scanning Electron Microscopy (SEM) revealed notable differences in porosity and surface texture following modification, indicating that the coating process successfully enhanced the physical properties of κ-carrageenan. These changes are expected to improve molecular interactions between the adsorbent surface and CR. Complementary analysis using Fourier Transform Infrared (FTIR) spectroscopy confirmed the introduction of new functional groups in mκC compared with uκC. Collectively, these findings demonstrate that chemical modification strengthened both the structural and chemical features of κ-carrageenan, which can be directly linked to its improved adsorption efficiency.

FTIR Analysis

The FTIR spectrum of uκC (Figure 1) showed only a few broad and weak absorption bands. Among the most distinct was a faint O–H stretching vibration near 3400 cm^{-1}, along with signals attributable to sulfate ester groups. Weak bands for C–O–C linkages and C=O stretching appeared between 1000 and 1050 cm^{-1}, reflecting a limited number of functional groups. In contrast, mκC displayed sharper and more intense peaks, confirming significant structural differences after modification. Key features included a strong C=O stretch at 1634 cm^{-1}, a broad O–H stretch at 3358 cm^{-1}, and a C–H stretch at 2923 cm^{-1}, confirming the successful incorporation of carbonyl groups. Additional peaks were observed at 1373 cm^{-1} (S=O), 1066 cm^{-1}(C–H bending), 1000 cm^{-1} (S–O stretching), and 602 cm^{-1} (O=C–N bending). These results verify that the modification process introduced sulfonate, amide, and nitrogen-containing groups, thereby enriching the surface chemistry of κ-carrageenan and improving its adsorption potential.

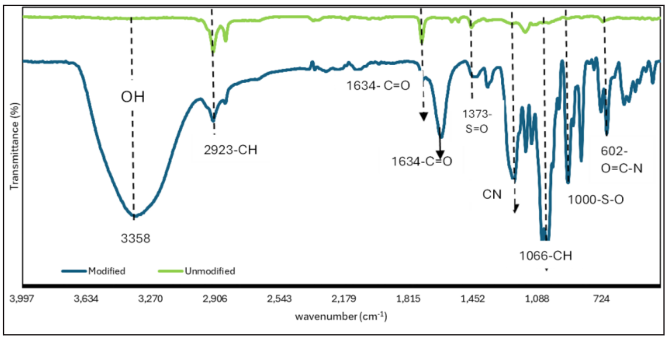
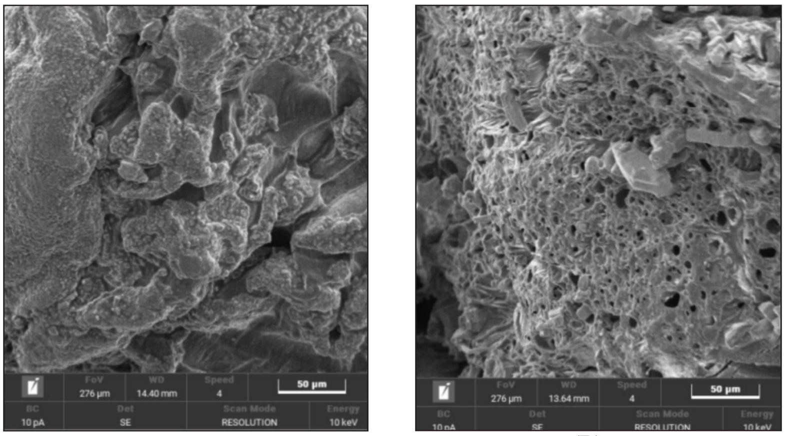


Figure 1. FTIR Spectra of uκC and mκC Adsorbent

Surface Morphology Analysis

SEM images (Figure 2) highlighted the clear structural contrast between uκC and mκC. The unmodified material exhibited a compact, smooth surface with pore sizes generally smaller than 5 μm, indicating low porosity. Such a dense structure restricts the accessibility of dye molecules, which likely contributes to reduced adsorption efficiency. In comparison, the modified adsorbent displayed a rougher surface with numerous cavities ranging from 5 to 20 μm. The appearance of these larger pores and enhanced surface roughness provides strong evidence of successful modification. These morphological changes are expected to increase surface interactions with CR molecules and thereby improve overall adsorption performance.



(A) (B)

Figure 2. SEM Images Depicting the Surface Morphology of (A) Unmodified κ-carrageenan, and (B) Modified κ-carrageenan.

Batch Adsorption Findings

To further compare adsorption behavior, batch studies were conducted under varying conditions of initial dye concentration, contact time, and adsorbent dosage. This allowed a direct performance evaluation of uκC and mκC composites.

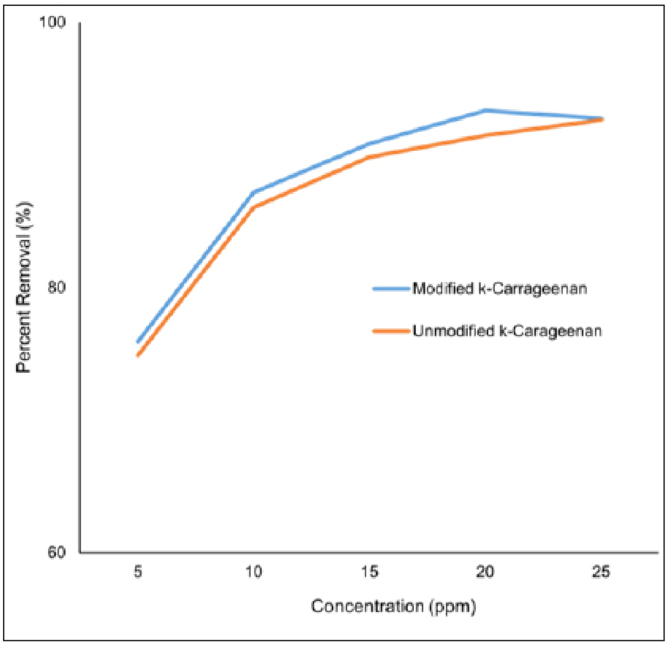


Figure 3. Effect of Initial CR Concentration (5 – 25mg/L) using 0.2g of uκC and mκC Adsorbent

Effect of Initial Concentration

The impact of initial dye concentration on adsorption was assessed in the range of 5–25 mg/L (Figure 3). Both materials showed high removal efficiency at lower concentrations, but the rate of improvement declined as the concentration increased, suggesting that adsorption sites were gradually approaching saturation. Across all concentrations, mκC consistently outperformed uκC, demonstrating greater capacity to handle different pollutant loads. At an initial CR concentration of 20 mg/L, mκC achieved its highest removal efficiency of 93.3%. Based on these promising results, mκC was selected for subsequent experiments examining the effects of contact time and adsorbent dosage.

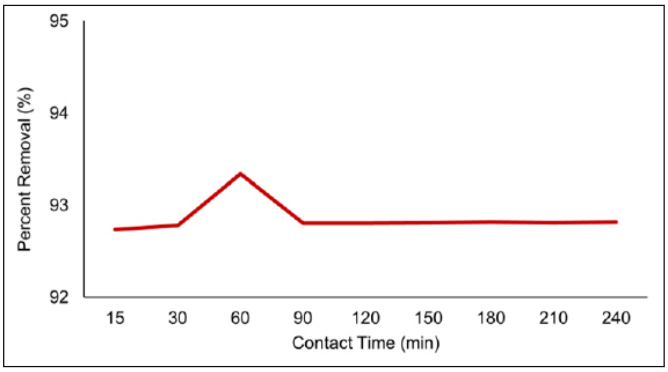


Figure 4. Effect of Contact Times (15 – 240 minutes) on Percentage Removal of CR using 0.2g mκC Adsorbent with 20 mg/L Initial Concentration

Effect of Contact Time

The study explored how the length of contact time affects the efficiency of removing CR over a span of 15 to 240 minutes, as shown in Figure 4. Initially, there was a noticeable jump in removal efficiency within the first 30 minutes. After that, the increase was more gradual, eventually reaching a peak efficiency of 93.3% at the 60-

minute mark. After 75 minutes, a noticeable decline in removal efficiency was observed, which subsequently stabilized over the remaining duration of the experiment. This behavior indicates that the available active sited on the surface of the adsorbent were rapidly saturated. This means that once those sites were filled, extending the contact time didn't significantly improve the removal efficiency.

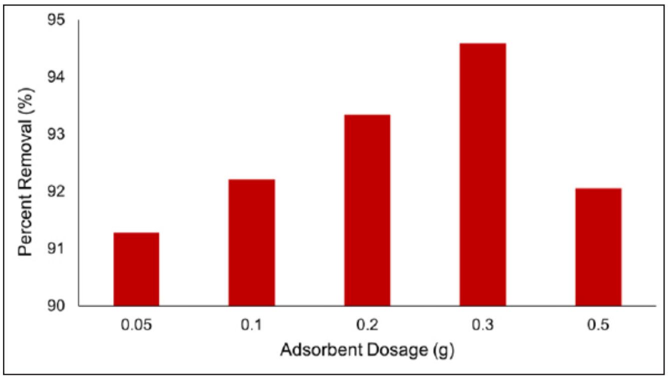
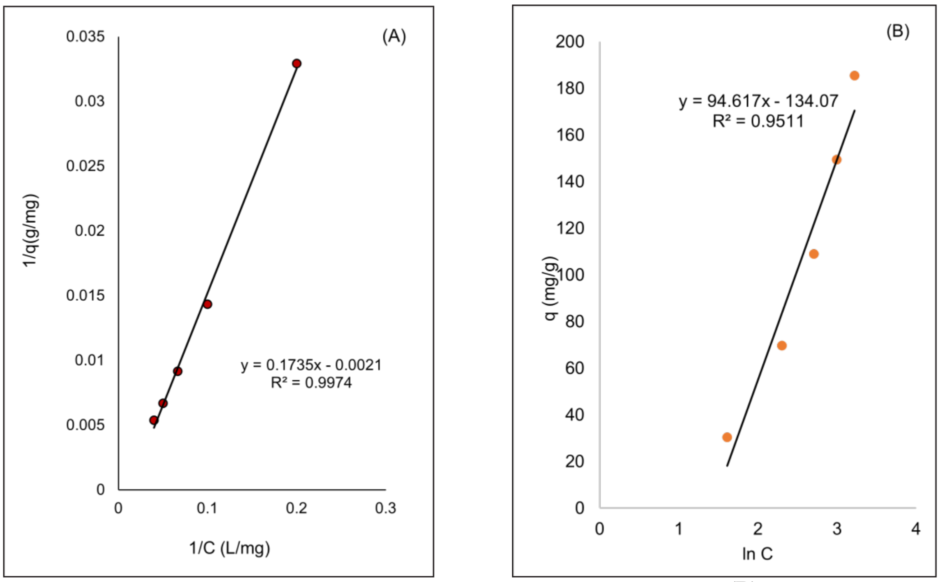


Figure 5. Effect of Biosorbent Dosage (0.05 - 0.5 g) on Percentage Removal of 20 mg/L CR using mκC Adsorbent

Effect of Adsorbent Dosage

The study looked at how different amounts of adsorbent affected the efficiency of dye removal, using varying dosages from 0.05 to 0.5 grams, as illustrated in Figure 5. It was noted that as the amount of adsorbent increased, the removal efficiency also improved. Specifically, the efficiency started at 91.29% with 0.05 grams and reached its highest point at 94.59% when 0.3 grams were used. It was observed that increasing the adsorbent dosage to 0.5grams resulted in a slight decline in removal efficiency, decreasing to 92.06%. This suggests that while adding more adsorbent generally helps by providing more active binding sites for dye removal, there's an optimal point beyond which the benefits seem to taper off. When the amount exceeds 0.3 grams, the efficiency tends to drop slightly. This could be attributed to particles clumping together or overlapping on the surfaces where they are meant to stick. As a result, the effective surface area decreases, leading to less effective use of the adsorbent.



(A) **(B)**

Figure 6. Adsorption Isotherms (A) Langmuir and (B) Temkin of CR onto mκC Adsorbent

Statistical Analysis

The study focused on analyzing the adsorption equilibrium data using Langmuir and Temkin isotherm models to understand how (CR) dye interacts with the mκC adsorbent, as shown in Figure 6. The Langmuir model displayed a strong fit, with a high correlation coefficient (R^2). From the linearized plot of 1/C against q_e, the calculated Langmuir constants were q_m of 476.19 mg/g and KL of 0.0121 L/mg, which were derived from the slope and intercept of the graph. The separation factor (RL) came out to be 0.805 when we tested it with an initial concentration of 20 mg/L of CR. Interestingly, the Temkin model fit the data really well, with a correlation coefficient (R^2) of 0.9511. The Temkin isotherm analysis yielded constants of BT being 94.617 mg/g and KT at 0.242 L/mg. These isotherm parameters are summarized in Table 1, which offers a clearer picture of the adsorption energetics and surface characteristics of mκC.

Table 1. Adsorption Isotherm Parameters for CR Adsorption

Langmuir		Temkin	
Parameters		Parameters	
q_m (g/mg)	476.19	B_T (mg/g)	94.617
K_L (L/mg)	0.0121	K_T (L/mg)	0.242
R^2	0.9974	R^2	0.9511
R_L	0.805		

DISCUSSION

Synthetic dyes discharged into aquatic systems represent a growing environmental challenge, particularly in sectors such as textiles, leather, paper, and printing. Among these, Congo Red (CR) is especially concerning. As an anionic diazo dye, CR possesses a complex molecular structure that resists natural degradation, allowing it to persist in the environment for extended periods (19). Its release not only disrupts aquatic ecosystems but also poses serious health hazards, with reported effects including mutagenicity, genotoxicity, and the generation of toxic aromatic amines through microbial breakdown. These risks underline the urgent need for low-cost and environmentally responsible methods to eliminate dyes from wastewater.

In this study, κ-carrageenan, a naturally occurring biopolymer, was chemically modified to improve its effectiveness as a biosorbent for Congo Red (CR) removal. The modification substantially enhanced its adsorption capacity, highlighting the potential of biopolymer-based adsorbents as practical solutions to pressing environmental and public health issues. Evidence from FTIR analysis confirmed notable structural alterations, particularly the successful incorporation of additional functional groups. While the unmodified form (uκC) displayed relatively weak spectral bands associated with O–H stretching, sulfate esters, and glycosidic C–O–C linkages, the modified material (mκC) exhibited clear signals corresponding to O–H, C=O, S=O, O=C–N, and C–H bending. These spectral changes indicate an enriched surface chemistry that provides a greater number of active sites capable of stronger and more diverse interactions with dye molecules (20-21).

The addition of these functional groups broadened the range of adsorption mechanisms available, including electrostatic attraction, ion exchange, and hydrogen bonding. Hydroxyl and carbonyl groups, for instance, can donate electron density, enabling hydrogen bond formation with the azo groups and sulfonic residues of CR (22). Similarly, functionalities such as S=O and O=C–N increase the polarity and hydrophilicity of the surface, facilitating faster diffusion of dye molecules and improving their anchoring onto the adsorbent. Collectively, these features emphasize the dominance of chemisorption in governing dye uptake by mκC. SEM imaging further validated these findings, showing clear differences in morphology between unmodified and modified materials. The surface of uκC appeared smooth and compact with little porosity, restricting accessibility for larger dye molecules such as CR. In contrast, mκC exhibited a rough, porous structure with cavities ranging between 5 and 20 µm (23). This transformation significantly increased the available surface area, allowing dye molecules to diffuse more efficiently and reach internal binding sites (24-25). Such morphological enhancements provide a strong explanation for the observed improvements in adsorption capacity.

The results of batch adsorption experiments reinforced these observations. Across all operating parameters—initial concentration, contact time, and adsorbent dosage—the modified κ-carrageenan consistently outperformed its unmodified counterpart. At an initial CR concentration of 20 mg/L, mκC achieved a maximum removal efficiency of 93.3%. This is particularly relevant for practical wastewater treatment, as typical industrial effluents contain dye concentrations ranging from 10 to 50 mg/L (26). Furthermore, equilibrium was achieved within 60 minutes, suggesting that active sites on the modified adsorbent were quickly occupied. Such rapid adsorption behavior is advantageous for both batch systems and continuous flow applications, where treatment efficiency and time are critical considerations (27).

The role of adsorbent dosage was equally notable. Removal efficiency improved substantially as the dosage increased from 0.05 g to 0.3 g, but a further increase to 0.5 g resulted in a slight decline. The slight reduction in efficiency at higher dosages can be attributed to particle aggregation, which reduces the effective surface area available for adsorption (28). Based on these findings, a dosage of 0.3 g appears to provide the optimal balance, achieving high removal efficiency while keeping material usage low—an important consideration for cost-effective wastewater treatment applications.

Overall, the results highlight mκC as an efficient and low-cost biosorbent with considerable potential for real-world application, particularly in textile and dye-intensive industries. However, it is important to recognize the limitations of this study. The experiments were conducted under controlled laboratory conditions, whereas industrial wastewater is often more complex. Variations in pH and ionic strength may alter adsorption efficiency by affecting the protonation state of functional groups and their electrostatic interactions with dye molecules. Additionally, the presence of competing ions or multiple pollutants in real effluents could reduce performance compared to single-solute systems. Future work should therefore evaluate the adsorbent under realistic wastewater conditions and investigate its reusability and long-term stability

These considerations highlight the need for further testing under real wastewater conditions to confirm the practical applicability of mκC in large-scale treatment settings. The promising performance of mκC indicates potential for application in larger wastewater treatment systems. However, scaling up introduces challenges such as ensuring the cost-effectiveness of raw κ-carrageenan, maintaining consistent modification quality, and preventing bead aggregation during continuous-flow operation (29). Although κ-carrageenan is widely available from marine sources and relatively inexpensive, future studies should evaluate supply chain stability, regeneration cycles, and cost-benefit analysis compared with conventional adsorbents. Such assessments are critical for industrial adoption, particularly in textile and dye-producing regions where wastewater treatment infrastructure may be limited (17).

The adsorption isotherm models, particularly the Langmuir and Temkin models, really help to understand how dyes interact with different adsorbents. This knowledge is crucial when it comes to developing effective water treatment systems. Ultimately, these advancements play a key role in protecting public health by ensuring cleaner water (30). In this study, the Langmuir model exhibited an excellent fit with R^2=0.9974, suggesting monolayer adsorption on a homogeneous surface, with a high q_m value of 476.19 mg/g (31-32). The R_L=0.805 suggests that CR can be efficiently and predictably removed under a wide range of environmental concentrations (33-34). When designing adsorption systems to maintain contaminant concentrations in treated water below toxic levels, high predictive accuracy is crucial. This is essential for lowering the possibility of human exposure through skin contact, drinking, or even crop irrigation. This objective is greatly aided by the Temkin model, which shows that chemisorption is necessary for the adsorption process. It displays a constant (K_T) of 0.242 L/mg and a maximum adsorption capacity (B_T) of 94.617 mg/g.

These findings point to a significant trend: the energy of adsorption tends to decrease as the adsorbent's surface coverage rises. The development of water treatment systems that put health and safety first can be greatly aided by this information (35–36). This lessens the likelihood that pollutants will be released and reintroduced, which is crucial for persistent contaminants like CR, which are known to be precursors to aromatic amines that cause cancer (37-38). In water systems impacted by dye contamination, these isothermal models are helpful tools for optimizing adsorbent efficacy, establishing operational limits, and protecting human and environmental health. The results raise significant health and environmental issues. Improper disposal of dye-laden effluents can result in significant water pollution, which affects aquatic life, the services these ecosystems offer, and even public health (39).

Because it can decompose through microbial processes into hazardous byproducts like benzidine and other aromatic amines, one particular compound, CR, is especially problematic. Significant health problems, such as liver troubles, bladder cancer, and disturbances in hormone functions, have been linked to these byproducts (40–41). Aquatic plants can suffer significant harm from dyes like CR because they block sunlight, which is necessary for photosynthesis. These dyes have the potential to accumulate in aquatic organisms over time, which could contaminate the entire food chain. The wellbeing of ecosystems and the species that depend on them may be significantly impacted by this (42). mκC prevents CR from accumulating in water systems by efficiently eliminating impurities and responding promptly. It's fantastic because, unlike some conventional chemical treatments or techniques that use activated carbon, it is non-toxic and biodegradable, meaning it doesn't contribute to further pollution. These frequently result in sludge or necessitate harsh chemicals for cleaning, so mκC is a far more environmentally friendly option (43).

κ-carrageenan is a natural polysaccharide that comes from marine sources, and it's quite popular in the food and pharmaceutical sectors. Its accessibility, compatibility with biological systems, and affordability make it a great option for developing larger-scale systems to treat dyes in commercial settings (44-45).The modification process described in this study is simple and safe, avoiding the use of toxic chemicals. This approach aligns with green chemistry principles, making it both environmentally friendly and effective. The findings contribute positively to the objectives of the United Nations Sustainable Development Goals, especially focusing on ensuring clean water and sanitation (SDG 6) and promoting responsible consumption and production (SDG 12).

The development of mκC-based technologies holds significant potential in promoting sustainable industrial practices. By improving access to clean water and minimizing the environmental footprint of various industries, these technologies are particularly valuable in low-resource settings where advanced treatment infrastructure is often lacking. Beyond supporting environmental sustainability, they also contribute to community well-being by ensuring the availability of essential resources. Nevertheless, certain limitations of the present study should be acknowledged. First, the work focused exclusively on a single model dye (Congo Red), which may limit the generalizability of the results to other pollutants. Future research should therefore explore the adsorption performance of mκC against a wider range of dyes and heavy metals to better assess its versatility. Second, the experiments were performed under batch conditions, which, although effective for controlled mechanistic evaluation, do not fully reflect the dynamic operation of real wastewater treatment systems that typically employ continuous flow processes. Validation of mκC under such practical conditions will be crucial to confirm its feasibility and scalability for industrial applications.

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CONCLUSION

In order to remove Congo Red (CR) dye from aqueous solutions, this study effectively demonstrated the enhanced adsorption capabilities of chemically modified κ-carrageenan (mκC). According to FTIR analysis, the addition of functional groups like carbonyl, sulfonate, and amide has greatly increased the adsorbent's chemical affinity for CR molecules. The modified adsorbent's increased surface roughness and porosity, as revealed by the SEM analysis, improved its adsorption efficiencyUnder ideal circumstances, which included an initial concentration of 20 mg/L, a contact time of 60 minutes, and a dosage of 0.3 g, batch experiments showed that mκC achieved a maximum removal efficiency of 93.3%. With a maximum capacity of 476.19 mg/g and R^2 = 0.9974, the Langmuir isotherm model best described adsorption equilibrium and monolayer adsorption. The involvement of chemisorption mechanisms was further validated by the Temkin model.

These findings establish mκC as an effective, biodegradable biosorbent with great potential for addressing CR dye pollution and mitigating its associated environmental and health risks. Beyond its adsorption efficiency, κ-carrageenan is inexpensive, renewable, and abundantly available from marine sources, making the modified form a potentially cost-effective alternative to conventional adsorbents in industrial wastewater treatment. Future research should focus on evaluating regeneration and reusability across multiple adsorption–desorption cycles to ensure long-term economic sustainability. Additionally, validating the performance of mκC in real industrial wastewater systems—where complex mixtures of pollutants, variable pH, and competing ions exist—will be essential for translating laboratory success into practical applications. Such efforts will not only strengthen the case for mκC in wastewater treatment but also contribute to advancing cost-effective and environmentally sustainable technologies for industrial effluent managemen

AUTHORS' CONTRIBUTION

WFWK: Writing- original draft, review & editing, Methodology, Formal Analysis. AA: Conceptualization, methodology, writing- review & editing, Supervision. NHMK: Writing- original draft, methodology. SH: Visualization, Investigation, Data Curation, Supervision. ARMA: Project administration, Supervision.

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