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Technopreneurship and Market Feasibility of Modified Carrageenan Hydrogel for Industrial Heavy Metal Remediation

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ABSTRACT

Heavy metal pollution in aquatic systems increases the need for sustainable and efficient natural adsorbent materials, and carrageenan extracted from Eucheuma cottonii, which contains O–H, S=O, C–O–S, and 3,6-anhydrogalactose functional groups, offers strong potential for binding metal ions. However, the adsorption efficiency of natural carrageenan for Copper (Cu^{2+}) and Cadmium (Cd^{2+}) ions remains limited, which frames the central problem of this study. In addressing this issue, **the method** employed involves synthesizing carrageenan hydrogel through alkaline extraction of Eucheuma cottonii and evaluating its adsorption capacity under controlled experimental conditions. The hydrogel was characterized and tested at pH 6–7, with a contact time of 90 minutes, an initial concentration of 200 mg/L, and an adsorbent mass of 6 g, followed by kinetic and isotherm modeling to analyze adsorption behavior. **Based on the Findings**, ionic exchange interactions between sulfate ester groups of K-carrageenan and metal cations significantly enhance adsorption performance, with the adsorption process following a pseudo-second-order kinetic model and the Freundlich isotherm providing the best fit $R^2 > 0.90$, indicating heterogeneous multilayer adsorption. In the **Conclusion**, the chemically modified carrageenan hydrogel demonstrates effective adsorption of copper and cadmium ions and presents strong potential as an eco-friendly and efficient biomaterial for heavy metal remediation.

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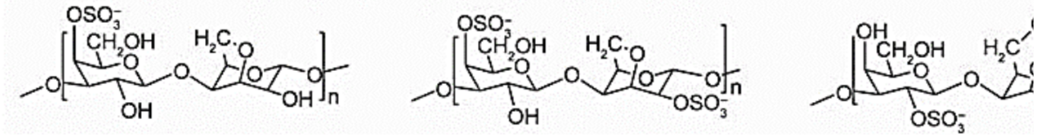
1. INTRODUCTION

Seaweed is a polysaccharide rich in nutrients and bioactive compounds, its dry weight contains 50% carbohydrates, 1-5% fat, 7-73% minerals, and 8-47% protein. These macroalgae are classified into Rhodophyceae, Chlorophyceae, and Phaeophyceae [1–3]. Carrageenan is a linear sulfated polysaccharide in the form of kappa, iota, and lambda extracted by alkali from seaweed [4, 5]. The types determine the characteristics and viscosity of carrageenan where these three types differ in the position and number of sulfate ester groups [6]. The structure of carrageenan is seen in Figure 1. Solid Liquid Extraction (SLE) is the initial stage for the manufacture of hydrocolloidal carrageenan. SLE is carried out by extracting active compounds in seaweed that have different solubilities using certain solvents. This contact causes a mass transfer process, in which the target compound gradually migrates from the solid phase into the solvent medium due to concentration gradients and intermolecular interactions [7, 8].



(a) (b) (c)

Figure 1. Carrageenan Structure: (a) Kappa, (b) Iota, and (c) Lambda

This method has drawbacks that are affected by the species of seaweed, the type of solvent, temperature, pH, and the desired extract. Then it needs to be optimized, especially on solvent use, extraction time, and co-extraction of interfering compounds [9, 10]. Extraction using acids or bases can be applied to minimize the amount of solvent and extraction time [11]. Seaweed grinding is also carried out to improve the efficiency of extraction by increasing the access of the solvent to the cell wall [12].

The results of the extraction are then gelated [5, 13]. In addition to being easily soluble in water, carrageenan contains sulfate groups that have specific properties as a gelling with high viscosity [6, 14, 15]. The quality of carrageenan gel is affected by the extraction result with alkali, where the alkali concentration has an impact on the sulfate content and gel strength. The addition of alkali will increase the molecular weight, convert L-galactose sulfate to 3,6-anhydrogalactose (3,6-AG), reduce sulfate ions, and produce a gel [16, 17]. In addition, the formation of carrageenan gel is also affected by the interaction and formation of a double helix due to the presence of specific ions in the form of univalent and divalent cations [18]. These cations act as polymer chain binders to produce stable gelation [3]. The bonding of sulfate ions on carrageenan with cations is seen in Figure 2.

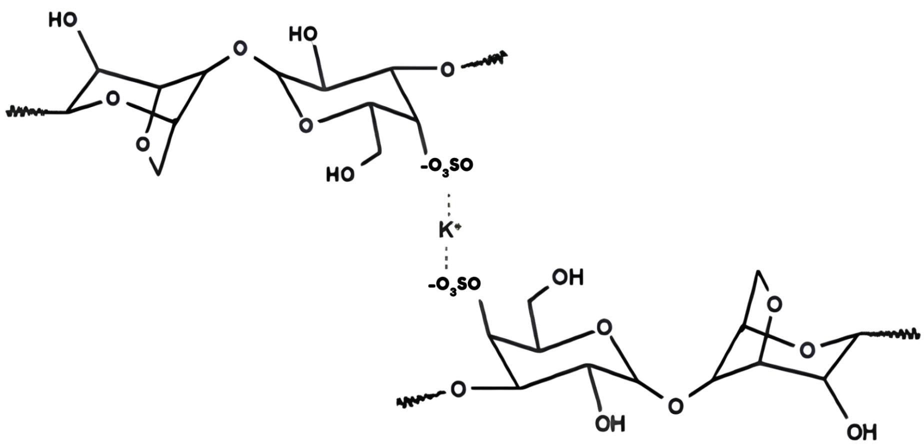


Figure 2. Bonding of Sulfate Ions in Carrageenan with K+ Ions

As an effective, efficient, and environmentally friendly biosorbent, Carrageenan is proposed to adsorb metal ions. According to Barquilha, carrageenan extract has a high absorption capacity because it has an active group. The sulfate group in the polysaccharide reacts with cations to form a hydrogel that has a good metal ion absorption capacity, and this adsorption is caused by the sulfate group interacting electrostatically with the cation [19–21]. Modified kappa-carrageenan hydrogels to increase adsorption capacity can also be done where influencing factors in the form of pH, contact time, and initial concentration need to be optimized [22, 23]. The development of Eucheuma cottonii hydrogel biosorbents from different aquatic locations is directed to produce strong and hard hydrogels through characterization and extraction [24]. The chemically modified products are then used to adsorb copper ions and cadmium ions by optimizing pH, contact time, initial concentration, and adsorbent mass and studying adsorption kinetics and adsorption isotherms [25, 26].

2. RESEARCH METHOD

Laboratory equipment used, namely: analytical balance, magnetic stirrers, hot plates, ovens, pH meters, blenders, thermometers, atomic absorption spectrophotometers, Fourier transform infrared spectrophotometers, and glassware. The materials used are potassium hydroxide, sodium hydroxide, hydrogen chloride, potassium chloride, copper nitrate, cadmium nitrate, filter paper, aquadest, and Eucheuma cottonii from the waters of the Kei Islands and West Seram in Maluku Province - Indonesia. The manufacture of hydrogel begins with repeated washing of Eucheuma cottonii to remove salt and other particles, then dried and mashed [27].

2.1. Formation of Carrageenan Hydrogels from Extraction Results

The formation of carrageenan hydrogels from Eucheuma cottonii extraction supports SDGS 12 because it utilizes renewable marine biomass as a sustainable raw material for water purification technologies. Eucheuma cottonii was extracted using an alkaline solvent with a controlled volume ratio at room temperature, and the initial pH was measured [28, 29]. The extraction results were filtered, and the liquid phase was decanted [30, 31]. The resulting carrageenan deposits were drained, acid-neutralized, filtered, and dried. Carrageenan was then dissolved in an aqueous medium and heated at 85–95°C until fully melted, producing a clearer and cleaner product [32, 33]. The hydrogel formed was separated from the liquid, and hydrogel formation was completed by adding chloride salts at room temperature [34–36]. This bio-based hydrogel material contributes to SDG 6 (Clean Water and Sanitation) by providing an environmentally safe option for heavy metal removal from contaminated water systems.

2.2. Optimization of pH, Contact Time, Initial Concentration, and Adsorbent Mass

Optimization of adsorption parameters directly supports SDGS 6 and SDGS 3, which aims to reduce pollution and improve water quality through sustainable treatment technologies. pH optimization was carried out by varying copper and cadmium ion solutions at pH 4, 5, 6, 7, and 8, respectively, and adding 1.0 g of hydrogel to each solution. The mixture was stirred, allowed to stand for 60 minutes, filtered, and the remaining concentration of metal ions was measured. Optimization of contact time, initial concentration, and adsorbent mass followed the same procedure to ensure maximum adsorption efficiency. This systematic optimization process ensures that the biosorbent operates in conditions closer to real wastewater scenarios, reinforcing its potential contribution to SDG 14 by reducing heavy metal discharge into aquatic ecosystems.

2.3. Capacity, Kinetics, and Adsorption Isotherms

The results of pH, contact time, initial concentration, and adsorbent mass optimization are then calculated as adsorption capacity (mg/g) and adsorption percentage (%) and then plotted to the curve [37, 38]. The adsorption capacity of metal ions is calculated using the equation:

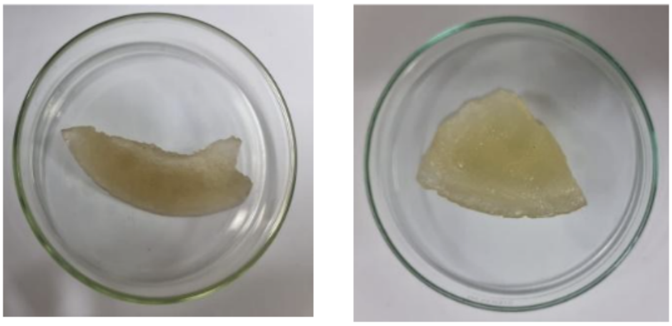
$$Q_c = \frac{(C_i \times V_i) - (C_f \times V_f)}{m} \quad (1)$$

Where: Qc is the adsorption capacity of metal ions (mmol/g), Ci is the initial concentration of metal ions (mmol/L), Vi initial volume (L), Cf is the final concentration of metal ions (mmol/L), Vf is the final volume (L), and m initial biosorbent weight (g). Adsorption kinetics were studied using pseudo-first-order and pseudo-second-order equations, while adsorption isotherms were studied using Langmuir and Freundlich models. The results of adsorption kinetics and adsorption isotherms are then plotted to the curve [28, 39, 40]. These analyses reinforced the hydrogel's performance reliability, supporting SDG 9 by advancing eco-friendly adsorbent technology. The strong adsorption performance indicates the hydrogel's potential for deployment in sustainable wastewater treatment systems aligned with global environmental goals.

3. RESULT AND DISCUSSION

3.1. Carrageenan Hydrogel

Hydrogels are produced through the extraction of carrageenan, a hydrocolloid composed of long-chain hydrophilic polysaccharides that exhibit strong water-binding capacities. These polysaccharides are capable of forming three-dimensional gel networks when they interact with specific cations, such as potassium or calcium ions, which promote helix formation and intermolecular aggregation [41, 42]. The physical appearance of carrageenan-based hydrogels derived from Eucheuma cottonii can be observed in Figure 3. Beyond biological and ecological factors such as habitat, seasonal variation, and seaweed maturity the functional properties of carrageenan hydrogels are also strongly influenced by the extraction techniques employed, including temperature, pH, and purification steps. Furthermore, the intrinsic characteristics of the seaweed, such as viscosity, sulfate content, and solubility, play a critical role in determining the final gel strength, elasticity, and stability of the hydrogel [1].



(a) (b)

Figure 3. Carrageenan Hydrogel (a) from the Kei Islands, (b) from West Seram.

Carrageenan is characterized by the presence of functional groups such as S=O, C–O–S, and 3,6-anhydrogalactose, which appear distinctly in the fingerprint region of the spectrum [43]. Characterization of Eucheuma cottonii is presented in Figure 4.

Figure 4. IR Spectrum Eucheuma Cottonii.

The results of carrageenan characterization produced three fingerprint absorption peaks at ±1200 cm-1 as the vibration of the sulfate ester group (S=O), ±920 cm-1 as the 3,6-anhydrogalactose ring, and ±840 cm-1 as the vibration of the galactose-4-sulfate (C-O-S) [44–46]. This absorption signal corresponds to the kappa-carrageenan structure [47]. Alkaline extraction using potassium ions as cross-linkers and the occurrence of hydrogen bonds between the OH groups of each monomer will cause a slight shift in the absorption signal [48].

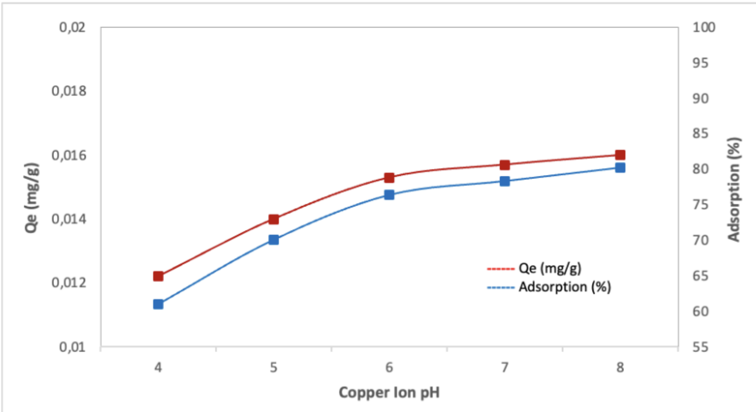
Table 1. Carrageenan Hydrogel from the Extraction Results.

Component	**Result**
Function clusters	*Eucheuma cottonii*, native to the Kei Islands and West Seram, has similar functional groups
Concentration and amount of extract	*Eucheuma cottonii* carrageenan extract from West Seram is more concentrated, but seaweed carrageenan from the Kei Islands produces more extracts
pH	Changes in the pH of seaweed carrageenan from the Kei Islands and West Seram occurred under the same conditions
Hydrogel strength	The seaweed carrageenan from the Kei Islands and West Seram produces a strong and hard hydrogel

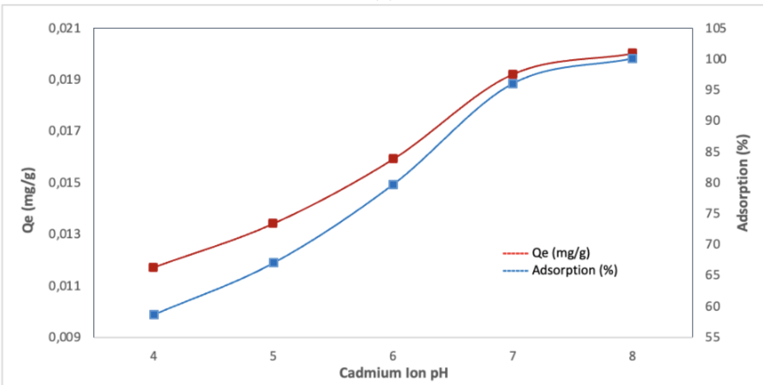
The extracted hydrogel is made using an alkaline solution and then precipitated with potassium chloride. The addition of potassium chloride aims to obtain a hydrogel with a strong and hard texture. For purification, the hydrogel is immersed in an aquifer and dented [41, 49]. Hydrogels from the extraction of Eucheuma cottonii carrageenan show similarities in active groups and physics-chemical properties Table 1.

3.2. Effect of pH, Contact Time, Initial Concentration, and Mass of Adsorbents

Adsorption occurs as a result of the electrostatic interaction between Copper (Cu^{2+}) and Cadmium (Cd^{2+}) ions with the anionic sulfate ester groups present in the carrageenan hydrogel matrix. The pH of the solution plays a crucial role in governing the strength and efficiency of this interaction. The curve illustrating the pH optimization results is shown in Figure 5. The optimization data indicate that the adsorption capacity and adsorption percentage increased progressively up to pH 6 for copper ions and pH 7 for cadmium ions, beyond which no significant improvement was observed. At lower pH levels, the sulfate ester groups undergo protonation, leading to an abundance of H^+ ions in the solution that compete with metal ions for the active binding sites, thereby reducing adsorption efficiency. Conversely, at higher pH levels, deprotonation of the anionic sulfate ester groups occurs, decreasing the concentration of H^+ ions and enabling stronger electrostatic attraction between the negatively charged hydrogel surface and the positively charged metal ions. This behavior demonstrates the pH-dependent mechanism of carrageenan hydrogels in metal ion adsorption processes, where variations in proton concentration directly influence the ionization state of sulfate ester groups, thereby controlling the electrostatic attraction and binding strength between the hydrogel matrix and the metal cations.



(a)

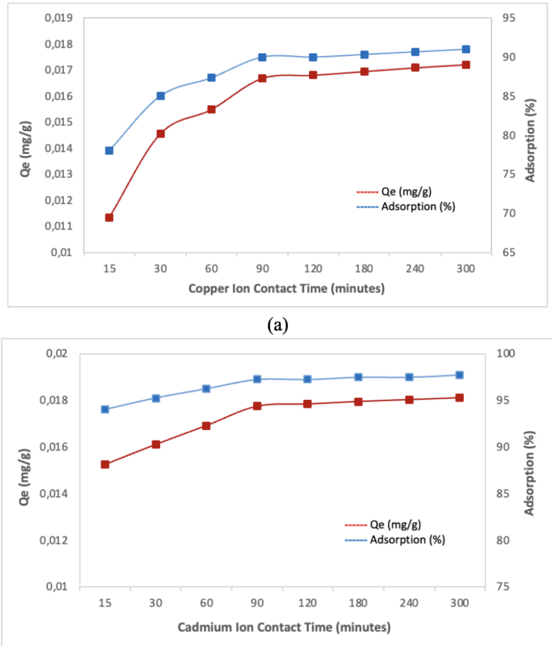


(b)

Figure 5. pH Optimization Curve: (a) Copper Ions and (b) Cadmium Ions.

The distinct optimal pH values observed for Cu^{2+} and Cd^{2+} can be attributed to the differences in their ionic radii, hydration energies, and binding affinities toward the sulfate ester groups. Copper ions bind more strongly due to their smaller size, while larger cadmium ions need a higher pH for effective adsorption.

Contact time optimization is carried out to determine the length of the adsorption process of copper ions and cadmium ions with adsorbents until equilibrium is reached. The curve of contact time optimization results is seen in Figure 6. The optimum contact time occurs at 90 minutes, where the increase in adsorption capacity and the percentage of adsorption is due to the length of the adsorbate interaction time with the adsorbent.

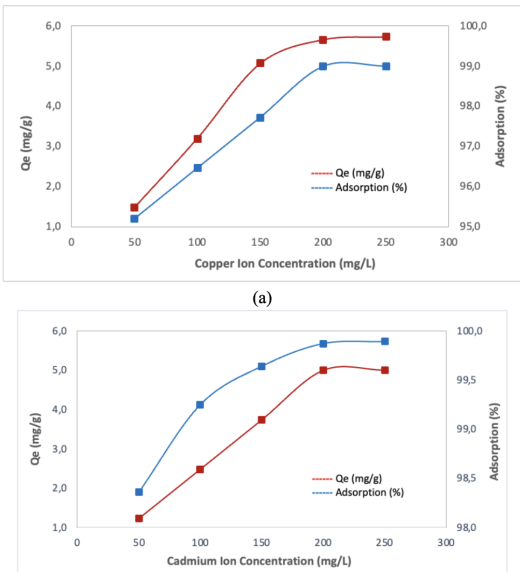


(a)

(b)

Figure 6. Contact Time Optimization Curves for (a) Copper Ions and (b) Cadmium Ions.

Initial concentration optimization aims to determine the maximum saturation level of carrageenan. The curve of the initial concentration optimization results is shown in Figure 7.



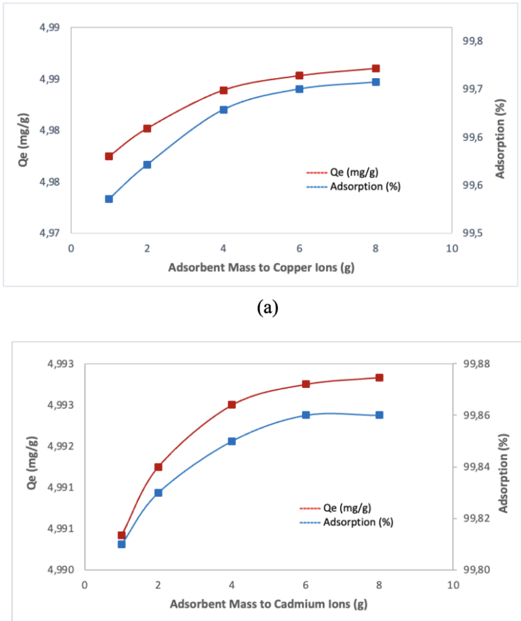
(a)

(b)

Figure 7. Initial Concentration Optimization Curves for (a) Copper Ions and (b) Cadmium Ions.

The optimization results show that the higher the initial concentration, the adsorption capacity value, and the adsorption percentage will increase; this is due to the presence of a number of active sites on the adsorbent surface. Initial concentrations of copper ions and cadmium ions were optimum at 200 mg/L. These optimum concentrations indicate the limitations of the hydrogel to adsorb metal ions.

Adsorbent mass optimization is carried out to determine the right mass for adsorption. A large adsorbent mass characterizes the number of active sites. The curve of adsorbent mass optimization results is shown in Figure 8.



(a)

(b)

Figure 8. The Adsorbent Mass Optimization Curves for (a) Copper Ions and (b) Cadmium Ions.

The optimum mass of hydrogel contacted with copper ions and cadmium ions is 6 grams, where an increase in adsorption capacity and adsorption percentage accompanies the increase in the mass of the hydrogel. At masses above 6 grams, the adsorption capacity and adsorption percentage did not experience a significant increase, indicating that equilibrium had been achieved.

3.3. Adsorption Kinetics and Adsorption Isotherms

Adsorption kinetics are used to determine the process of diffusion of metal ions in hydrogels using pseudo-first-order or pseudo-second-order models.

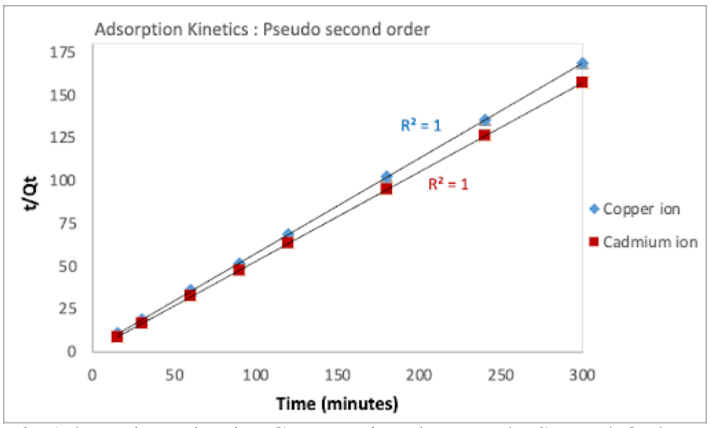


Figure 9. Adsorption Kinetics Curve Using the Pseudo-Second-Order Model.

Adsorption isotherms are performed to estimate the adsorption process on the surface of the hydrogel based on the Langmuir or Freundlich models. Contact time and initial concentration optimization data were used to study adsorption kinetics and adsorption isotherms Figure 9 and Figure 10.

The results of the kinetic linear fitting for the adsorption of copper and cadmium ions demonstrate that the pseudo-second-order model provides an excellent representation of the adsorption mechanism, with both ions exhibiting correlation coefficient (R^2) values of 1.0 Figure 9. Such a perfectly linear relationship indicates that the adsorption rates are primarily governed by chemisorption processes involving valence forces, electron sharing, or exchange between functional groups within the hydrogel matrix and the metal ions. In contrast, the pseudo-first-order model yielded significantly lower R^2 values of 0.8147 for copper and 0.7017 for cadmium, suggesting a poor fit and implying that physisorption or diffusion-limited mechanisms do not predominantly control the adsorption behavior. These findings collectively confirm that the adsorption of both copper and cadmium ions onto carrageenan-based hydrogels follows pseudo-second-order kinetics, reflecting a strong affinity and a reaction rate dependent on the availability of active binding sites on the hydrogel surface.

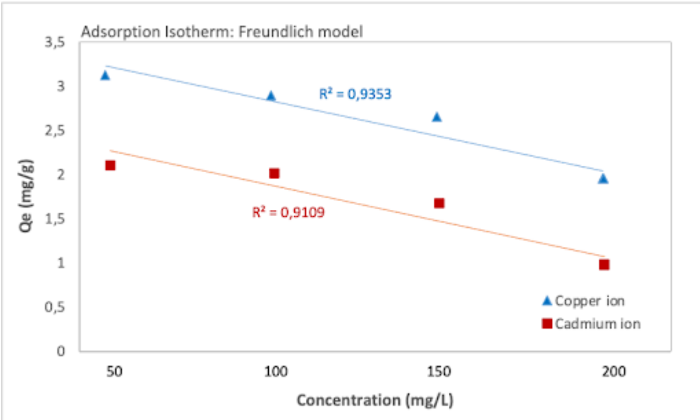


Figure 10. Adsorption Isotherm Curves Using the Freundlich Model.

The results of the Freundlich model linear fitting for both copper and cadmium ions show that the correlation coefficients (R^2) are close to 1, indicating a strong agreement between the experimental adsorption data and the Freundlich isotherm. In comparison, the Langmuir model produced substantially lower R^2 values of 0.5687 for copper and 0.5405 for cadmium, demonstrating a poor fit and suggesting that monolayer adsorption on a homogeneous surface is not the dominant mechanism. The superior performance of the Freundlich model implies that the carrageenan-based hydrogel possesses a heterogeneous surface with multiple types of active binding sites, enabling multilayer adsorption of both ions. This heterogeneity may arise from variations in functional groups, surface roughness, or structural irregularities within the hydrogel matrix, all of which contribute to the differential affinity of the surface sites toward metal ions. Thus, the adsorption process is better described as a non-ideal, multilayer interaction consistent with the characteristics of the Freundlich isotherm.

4. MANAGERIAL IMPLICATION

The findings highlight that Eucheuma cottonii-based carrageenan hydrogels offer a sustainable and cost-effective solution for heavy metal remediation. Industrial managers can apply the optimized parameters (pH 6–7, 90-minute contact time, and 6 g adsorbent mass) to improve wastewater treatment efficiency. For technopreneurs, the utilization of local seaweed resources presents an opportunity to develop eco-innovative products with high market potential. Policymakers are encouraged to support bio-based technologies that enhance environmental performance and promote sustainable industrial practices. For environmental and production managers, the optimized adsorption parameters identified in this research pH 6–7, a 90-minute contact time, and an adsorbent mass of 6 gramscan serve as practical operational guidelines for implementing biosorption systems in industrial wastewater treatment processes. Understanding the pH-dependent adsorption mechanism allows managers to design treatment processes that maximize efficiency while minimizing chemical usage and operational costs. The integration of carrageenan-based hydrogels into existing treatment systems could significantly enhance compliance with environmental standards and improve corporate sustainability performance indicators. For technopreneurs and business innovators, these findings highlight new market opportunities for developing sustainable products derived from Eucheuma cottonii. The transformation of seaweed biomass into value-added adsorbent materials supports the growth of green industries and can create new income streams for coastal communities engaged in seaweed cultivation. Such innovation aligns with national priorities for blue economy development and provides competitive advantages in the emerging global market for eco-technologies. From a policy and strategic management perspective, the study underscores the need for supportive frameworks that promote research, innovation, and commercialization of bio-based materials. Policymakers are encouraged to incentivize collaborations between academic institutions, local industries, and small enterprises to accelerate the adoption of sustainable technologies. Strengthening these partnerships can foster environmental innovation, reduce industrial pollution, and enhance national competitiveness in the field of green manufacturing and waste management.

5. CONCLUSION

Carrageenan hydrogel derived from Eucheuma cottonii has been demonstrated to be effective in adsorbing copper and cadmium ions due to its abundant sulfate ester functional groups and anionic surface characteristics. The modification of the hydrogel through optimized extraction and preparation parameters specifically pH adjustment to approximately 6–7, a contact time of 90 minutes, an initial metal concentration of 200 mg/L, and an adsorbent mass of 6 grams significantly enhances the density and accessibility of active binding sites. These optimized conditions strengthen the electrostatic interactions between the negatively charged hydrogel surface and divalent metal cations, ultimately improving both adsorption capacity and removal efficiency for the two ions.

The findings of this study indicate that carrageenan-based hydrogels can serve as environmentally friendly, biodegradable, and cost-effective adsorbents suitable for heavy metal remediation in aqueous systems. However, further research is required to evaluate the hydrogel's long-term stability, regeneration efficiency, and adsorption performance under dynamic or real wastewater conditions. Future studies should also investigate the incorporation of additional functional groups, composite formation with biochar or nanoparticles, and modeling approaches to better understand the adsorption mechanism at the molecular scale.

The implications of these results are significant for the development of sustainable water purification technologies, particularly in regions facing heavy metal contamination from industrial effluents. The enhanced carrageenan hydrogel has the potential to be integrated into filtration units, adsorption columns, or hybrid treatment systems to support cleaner production and environmental protection. By advancing material optimization and scaling up production, this hydrogel could contribute to more accessible and eco-friendly solution

6. DECLARATIONS

6.1. About Authors

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6.2. Author Contributions

Conceptualization: YH, LI, HE, MB and GA; Methodology: GA, LI and HE; Software: LI, and NB Formal Analysis: GA, LI, MB and YH; Investigation: YH, LI and MB; Resources: MB, LI, and HE; Data Curation: GA, LI and HE; Writing Original Draft Preparation: LI and HE; Writing Review and Editing: YH, LI, and MB; Visualization: YH, LI, and HE; All authors, YH, LI, HE, MB, and GA have read and agreed to the published version of the manuscript.

6.3. Data Availability Statement

The datasets used to support the findings of this study are available from the direct link in the dataset citation.

6.4. Funding

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6.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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