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Adsorptive Removal of Nickel Ions by Sodium Alginate-Modified Waste Cotton Fabric

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ABSTRACT

The development of low-cost adsorbents for the simple and efficient adsorption of metal ions is challenging but of great significance for meeting the strict requirements of environmental protection. The current study focused on the development of a low-cost adsorbent material through the functionalization of waste cotton fabric with sodium alginate (SA), optimization of SA concentration for maximum adsorption of nickel ion, and study of the effects of important parameters such as contact time, pH, initial nickel concentration, and temperature on adsorption performance. The modification was performed by alkaline pre-treatment followed by immersion in different concentrations of SA (0.1- 0.9 wt%). The coating ratio was increased stepwise from 6.1% to 18.3% as the SA concentration increased. The optimum SA concentration was determined, and importantly, the SA-modified waste cotton fabric with 0.7 wt% SA exhibited a high adsorption capacity of 494 mg/g and attained equilibrium in 5 hours. The adsorption performance was pH-dependent, with maximum uptake at pH 6.0. The temperature had little influence on the adsorption efficiency in the range of 20-50°C. Considering the excellent adsorption performance of this modified waste cotton fabric, this simple and novel strategy may open a new avenue for developing sustainable, cost-effective adsorption materials to meet the growing demand for rapid, efficient metal-ion adsorption.

1. Introduction

Nickel ions are a type of non-biodegradable, toxic, heavy metal that is widely used in electroplating, battery manufacturing, and the mining industry. These ions are often present in wastewater at concentrations of 1-1.5 g/L (Baby et al., 2022; Bartzas et al., 2021). In addition to their environmental persistence, these ions are also highly hazardous to human health, including dermatitis and allergic sensitization (Ahlström et al., 2019; Rafati Rahimzadeh et al., 2025). Thus, the effective removal of nickel from industrial effluents has become a critical priority for environmental safety and public health.

Currently, various techniques are used to remove nickel ions, including chemical precipitation, filtration, membrane separation, and adsorption (Kruszelnicka et al., 2022; Vakili et al., 2021). Among these, adsorption is preferred for its cost-effectiveness, simplicity of operation, and high efficiency (Rashid et al., 2021). Biopolymer-based adsorbents from renewable, biodegradable sources, such as cotton, may be an environmentally sustainable alternative to synthetic polymers and help avoid secondary pollution (Latif et al., 2025; Ma et al., 2018; Mohanrasu et al., 2025; Zhang et al., 2008). However, the pristine waste cotton fabric suffers from inherent disadvantages, such as a low adsorption capacity because of the limited number of active sites (mainly hydroxyl groups with weak affinity to metals), sluggish kinetics due to the restricted mass transfer, and a high pH sensitivity because of the narrow deprotonation window of cellulose hydroxyl groups.

To address this issue, cotton has been modified using various agents, including tetraethylenepentamine (Niu et al., 2019), oxide nanoparticles (Yu et al., 2014), and epoxypropyltrimethylammonium chloride (Jiang et al., 2023). Nevertheless, the high cost and complicated synthesis of these agents limit their practical applications (Xu et al., 2015). Sodium alginate (SA) is a biopolymer derived from brown algae and is an attractive alternative due to its biocompatibility, biodegradability, and abundant hydroxyl and carboxyl groups that serve as suitable metal-binding sites (Ahmad et al., 2021; Bairagi et al., 2023; Ling Felicia et al., 2025; Shi et al., 2022). However, SA alone has low mechanical strength and stability; chemical functionalization of SA onto cotton fabric is a promising approach to combine the robust physical structure of cotton with SA's superior metal-chelating capacity (Li et al., 2018).

Recently, some adsorbents for nickel were reported, such as chitosan-coated cotton fibers (~45 mg/g) and cationic waste cotton fabric, which required complicated synthesis processes (Jiang et al.,

2023; Zhang et al., 2008) Unlike these approaches, our SA-functionalized waste cotton fabric takes advantage of a high density of carboxyl groups that remain negatively charged over a broader pH range, thereby improving binding affinity for nickel ions, increasing adsorption kinetics by enhancing hydrophilicity, and decreasing pH sensitivity. Therefore, in this study, we aimed to develop a low-cost, high-performance adsorbent based on SA-functionalized waste cotton fabric. The specific objectives were: (i) to optimize the SA concentration for maximum adsorption capacity; (ii) to characterize the interaction between SA and cotton fabric; (iii) to evaluate the adsorption performance under different experimental conditions; and (iv) to elucidate the mechanism of nickel ion capture by chemical coordination.

2. Materials and methods:

2.1 Materials:

SA, NaOH, and nickel sulfate hexahydrate ($NiSO_4 \cdot 6H_2O$) were purchased from Shanghai Lingfeng Chemical Reagent Co., Ltd., Shanghai, China. 100% waste-cotton plain-woven fabric (350 g/m², 15 picks x 40 ends/cm) was purchased from Sur International Investment Co., Ltd.

Scheme 1. Schematic of the experimental strategy, including the fabrication of SA-modified waste cotton fabric and the adsorption of nickel ions using the SA-modified waste cotton fabric

2.2. Surface Modification of Waste Cotton Fabric

The surface modification of waste cotton fabric with SA was conducted following the methodology established by Bhuiyan et al. (2017), beginning with a crucial pre-treatment step to prepare the fabric for effective modification. Initially, the waste cotton fabric was subjected to alkaline scouring, in which it was boiled in a 4 g/L sodium hydroxide solution for 45 minutes at a liquor-to-material ratio of 20:1 to ensure complete removal of fats, waxes, and other natural impurities that could impede subsequent reactions. Following this purification stage, the fabric was dried at 80°C for 20 minutes to remove residual moisture, thereby creating a pristine, receptive substrate for modification.

Subsequently, the actual surface modification was performed by treating the pre-cleaned fabric with SA concentrations of 0.1, 0.3, 0.5, 0.7, and 0.9 wt%. For each concentration, the SA solution was prepared at room temperature by dissolving the precise amount of SA powder in distilled water, after which 5×5 cm pieces of the prepared waste cotton fabric were immersed in these solutions for 3 hrs to facilitate adequate interaction between the cellulose fibers and the SA molecules. Upon completion of the treatment, the SA-modified fabrics were thoroughly rinsed with distilled water in multiple cycles to remove any unbound or excess SA residue, ensuring that only chemically bound succinic acid remained on the fabric surface. Finally, the modified fabrics were dried again at 80°C for 20 minutes, rendering them ready for subsequent characterization and application, thereby completing a systematic and reproducible modification process to enhance the functionality of waste cotton textiles.

2.3. Characterization:

2.3.1. Surface Modification

The coating ratio (%) was calculated by using the equation:

$$Coating\ ratio\ (\%) = \frac{(W - W_\circ)}{W_\circ} * 100 \quad (1)$$

Where: W represents the weight of fabric after coating, and W° represents the weight before SA coating.

2.3.2. Preparation of the Nickel Ion Standard Curve

To construct a reliable calibration curve for quantitative analysis, a standard solution of nickel ions was meticulously prepared over a concentration range of 0.5-5 µg/mL in 0.5 µg/mL increments. The absorbance of each standard was then measured using a UV-Vis spectrophotometer, thereby establishing a robust absorbance standard curve. This curve serves as a fundamental reference, illustrating the direct correlation between nickel ion concentration and absorbance, thereby enabling accurate determination of unknown samples based on their spectrophotometric response.

2.3.3. The Effect of SA on the Nickel Ion Adsorption

To investigate the adsorption properties of the modified cotton fabrics, a stock solution of nickel ions was first prepared by dissolving nickel(II) sulfate hexahydrate ($NiSO_4 \cdot 6H_2O$) to obtain a precise concentration of 0.5 µg/mL. Subsequently, 5-gram samples of cotton fabrics modified with varying SAx concentrations (0.1, 0.3, 0.5, 0.7, and 0.9 wt %) were individually immersed in the prepared

nickel solution. The mixtures were then agitated at a controlled temperature of 25°C to facilitate adsorption. Following this period, the final nickel ion concentration in each solution was measured. These values were then used to determine the adsorption capacity of each fabric sample, calculated as the difference in ion concentration using the provided standard formula.

$$q = \frac{(C_\circ - C_e)V}{M} \qquad (2)$$

Where: q: the amount of Nickel ions adsorbed (mg/g), $C_\circ$: Initial concentration of Nickel ions solution (mg/L), C_e: Nickel ions solution concentration after adsorption (mg/L), V: Volume of Nickel ions solution (L), and M: mass of cotton fabric (g)

Additionally, the effects of pH, time, temperature, and concentration on Nickel ion solutions were examined by exposing 5 g of cotton fabric to 50 mL of each solution. The pH values were adjusted using 0.5 M HCl and 0.5 M NaOH; effects at higher pH values were not recorded because Nickel hydroxide precipitated.

It should be noted that the nickel ion solutions used throughout this study were laboratory-simulated wastewaters prepared by dissolving nickel(II) sulfate hexahydrate ($NiSO_4 \cdot 6H_2O$) in deionized water at specified concentrations.

Preliminary optimization for this study revealed a fixed adsorbent dosage of 5 g. However, the adsorption performance was affected by the adsorbent dosage due to the density of the available binding sites and removal efficiency. The normalized adsorption capacity q (mg/g) is corrected for dosage differences, but the effect of dosage in the range 1–10 g/L should be systematically investigated in future work to determine the optimal mass-to-volume ratio for practical use.

2.3.4. Adsorption calculation

(1) Kinetic parameters

We studied the adsorption kinetics of nickel ions, constructed pseudo-first-order (PFO), pseudo-second-order (PSO), and intraparticle diffusion (IPD) kinetic models, and calculated the kinetic parameters.

$$\log(Q_e - Q_t) = \log Q_e - K_1 t / 2.303 \qquad (3)$$

Where Q_e and Q_t are the amount of nickel ion adsorbed on L-CNF at equilibrium and time t (mg/g), and K_1 is the rate constant of first-order adsorption (min^{-1}).

$$t/Q_t = 1/(k_2 Q_e^2) + t/Q_e \qquad (4)$$

Where K_2 is the rate constant of second-order adsorption (g $mg^{-1}min^{-1}$).

$$Q_t = K_i t^{0.5} + C \qquad (5)$$

Where Ki is the intraparticle diffusion rate (mg $g^{-1}min^{-0.5}$). C (mg/g) is a parameter related to the thickness of the boundary layer in intraparticle diffusion.

(2) Thermodynamic and Isotherm parameters

The thermodynamic parameters are obtained by fitting the three equations.

Langmuir adsorption isotherm

$$C_e/Q_t = 1/(K_l Q_m) + C_e/Q_m \qquad (6)$$

Freundlich adsorption isotherm

$$\log Q_e = 1/n \log C_e + \log K_f \qquad (7)$$

Temkin adsorption isotherm models

$$Q_e = A + B \ln C_e \qquad (8)$$

Where Qmax (mg/g) is the theoretical maximum adsorption capacity; KL (L/mg) is the Langmuir balance parameter; Kf ($mg^{1-1/n}$ $L^{1/n}$ g^{-1}) and n are the Freundlich constants concerning the adsorption capacity and intensity, respectively; the values of A and B can be determined from the slope and intercept of the linear plot of Q_e vs. ln C_e.

3. Results and discussion

3.1. Surface Modification of Waste Cotton Fabric

To develop an effective waste cotton fabric-based adsorptive material for removing nickel ions from aqueous solutions, this study explored an innovative approach: functionalizing the fabric with sodium alginate (SA), a surface-modification strategy that had not been extensively investigated in the literature. The interaction between sodium alginate and waste cotton fabric is primarily governed by hydrogen bonding and electrostatic interactions. Cotton cellulose possesses abundant hydroxyl (-OH) groups along its polymer backbone, while sodium alginate contains both hydroxyl and carboxyl (-COOH) functional groups. Upon immersion of the pre-treated cotton fabric in SA solution, hydrogen bonds formed between the hydroxyl groups of cellulose and the hydroxyl/carboxyl groups of SA molecules. Additionally, the alkaline pre-treatment step (4 g/L NaOH) partially converted cellulose hydroxyl groups to alkoxide ions ($-O^-$), creating negatively charged sites on the fabric surface. These negatively charged sites interact electrostatically with the sodium ions associated with alginate carboxylate groups ($-COO^-$ Na^+), facilitating strong adhesion of the SA coating. Furthermore, weak van der Waals forces contributed to the physical adsorption of SA onto the fiber surface. This multi-modal interaction mechanism, combining hydrogen bonding, electrostatic forces, and van der Waals interactions, ensured stable immobilization of SA onto the cotton fabric without the need for chemical crosslinkers, thereby maintaining the cost-effectiveness of the modification process. As the SA concentration increased, more SA molecules assembled on the fiber surface, forming a thicker coating layer, as evidenced by the increasing coating ratios presented in Table 1. The data revealed a clear, progressive increase in the weight of the cotton fabric following SA surface modification, providing direct evidence of polymer deposition. Specifically, as the concentration of the SA coating solution was incrementally increased from 0.1 to 0.9 wt%, the resulting weight of the treated cotton fabric rose from 0.82±0.01 g to

0.97±0.04 g. This mass gain translated directly into an increase in the coating ratio, which rose from 6.1±0.03% at the lowest concentration to 18.3±0.02% at the highest concentration. This observed phenomenon could be attributed to the mechanism of coating formation, in which SA molecules assembled on the surface of cotton fibers. As the concentration of the SA solution increased, more polymer chains were available to interact with the fabric's cellulose backbone, resulting in a thicker, more densely packed SA coating. This established correlation between SA concentration and coating ratio is fundamental, as a thicker coating layer is expected to provide a higher density of functional carboxyl and hydroxyl groups, the primary active sites responsible for chelating and adsorbing nickel ions, thereby underpinning the material's enhanced performance in wastewater treatment applications.

Table 1. The coating ratio of cotton fabric coated with different SA concentrations.

SA concentrations (wt%)	Weight after coating (g)	Coating ratio (%)
0.0	0.82±0.01	00.0±0.0
0.1	0.84±0.02	2.4±0.02
0.3	0.87±0.04	06.1±0.03
0.5	0.90±0.04	09.8±0.01
0.7	0.94±0.03	14.6±0.03
0.9	0.97±0.04	18.3±0.02

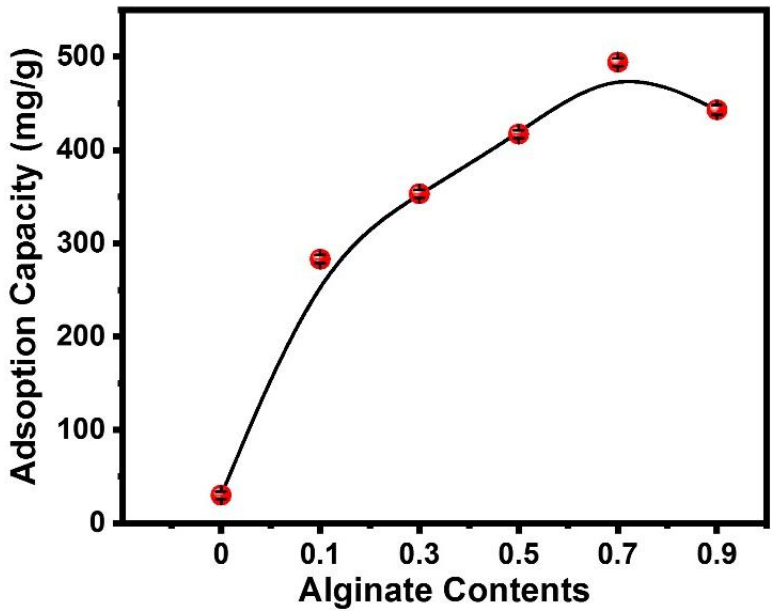

Figure 1. Nickel Ion Adsorption Performance of SA-modified cotton waste cotton fabric with various SA concentrations

3.2. Impact of SA Contents on Adsorption Performance

The adsorption capacity of the modified cotton fabric was fundamentally governed by the electrostatic interaction between the negatively charged carboxyl groups on the sodium alginate (SA)-coated surface and the positively charged nickel ions in solution, meaning that the density of available carboxyl binding sites directly dictated the material's overall uptake performance. To systematically explore this relationship, the effect of varying SA content on adsorption efficiency was rigorously evaluated, and the results are presented in Figure 1. Notably, as the SA concentration increased, the adsorption quantity increased consistently, peaking at 494 mg/g in the sample coated with 0.7 wt% SA. This marked enhancement could be attributed to the greater availability of SA macromolecules on the fabric surface, which introduced a higher density of carboxyl functional groups, thereby providing numerous accessible binding sites for nickel ion capture and facilitating efficient ion transfer. However, this trend did not persist indefinitely; when the SA concentration was further raised to 0.9 wt%, the adsorption capacity declined to 443 mg/g. This reduction likely stemmed from the formation of an excessively thick or densely packed SA layer at elevated concentrations, which might have obstructed some active sites or created a physical barrier that impeded the diffusion of nickel ions into the coating's inner regions. Consequently, based on the observed trade-off between site availability and mass-transfer limitations, 0.7 wt% SA was identified as the optimal coating concentration, striking the most effective balance to maximize adsorption performance under the tested conditions.

3.3. The Optimization of Nickel Ion Adsorption

The experimental conditions for nickel ion adsorption were carefully optimized to maximize the adsorption capacity of sodium alginate (SA)-modified cotton fabric. As previously established, the proposed adsorption mechanism relied on electrostatic interactions between the negatively charged carboxyl groups on the SA-modified cotton surface and the positively charged nickel ions in solution. Given the nature of this ionic attraction, the overall efficiency of the process was expected to be influenced by several key environmental and operational parameters. To

systematically evaluate the material's performance and identify ideal conditions for practical use, this study investigated the effects of contact time, solution pH, initial nickel concentration, and temperature on the adsorption capacity of the modified fabric.

The kinetics of nickel ion adsorption were first examined by measuring the uptake capacity of the SA-modified cotton fabric (0.7 wt%) at regular time intervals, and the results are presented in Figure 2a. The data revealed a rapid increase in adsorption during the initial stages, followed by a gradual plateau as equilibrium was approached. Specifically, adsorption equilibrium was reached within approximately four hours, after which no significant increase in uptake was observed beyond six hours. This behavior indicated that the binding sites on the fabric surface became saturated over time. Importantly, the modified fabric exhibited considerably faster adsorption kinetics than unmodified cotton, a result attributed to the abundant functional carboxyl groups introduced by the SA coating. The rapid attainment of equilibrium not only reflected the material's high affinity for nickel ions but also underscored its practical potential for applications requiring fast, efficient metal-ion removal.

Solution pH is another critical factor governing adsorption efficiency, as it directly influences both the adsorbent surface charge and the speciation of metal ions in solution. As shown in Figure 2b, the adsorption capacity of the SA-modified cotton fabric was evaluated across a pH range of 0.5 to 6.0, with the upper limit selected to prevent the precipitation of nickel hydroxide at alkaline conditions. The results demonstrated a strong dependence on pH: adsorption remained minimal under highly acidic conditions (pH < 3), largely due to competition between excess hydrogen ions and nickel ions for the limited number of accessible binding sites. As the pH increased, however, the carboxyl groups on the fabric surface became increasingly deprotonated, thereby increasing the negative charge density and the electrostatic attraction to Ni^{2+} ions. Maximum adsorption was observed at pH 6.0, confirming the importance of maintaining weakly acidic to neutral conditions for optimal performance.

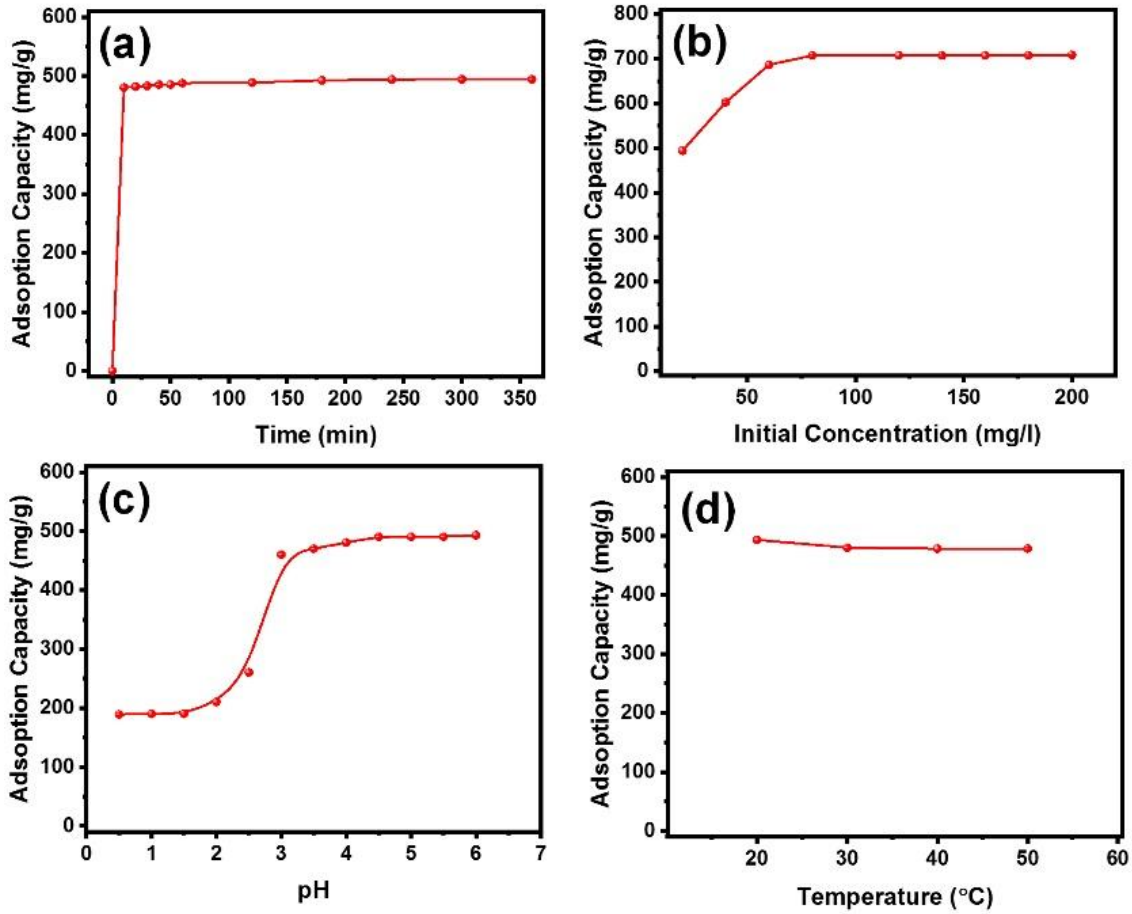

Figure 2. Effect of (a) time, (b) initial concentration of Nickel ions (the higher values (up to 708 mg/g) were obtained under different initial concentration conditions (20-200 mg/L range) and represented capacity under non-equilibrium conditions or reflected the effect of a concentration gradient), (c) pH value, and (d) temperature on the adsorption performance of the SA modified waste cotton fabric

The initial concentration of nickel ions also plays a pivotal role in determining the adsorption capacity, as it provides the driving force to overcome mass-transfer resistance between the liquid and solid phases. To assess this effect, experiments were conducted over a range of initial concentrations from 20 to 200 mg/L, and the results are illustrated in Figure 2c. The adsorption capacity increased steadily with increasing

initial nickel concentration, rising from 493.7 mg/g at 20 mg/L to 708 mg/g at 200 mg/L. This trend suggested that at lower concentrations, the available binding sites were sufficient to accommodate nearly all incoming ions, while at higher concentrations, the enhanced concentration gradient facilitated greater utilization of adsorption sites. The sustained high capacity across this range highlighted the material's effectiveness even under elevated contaminant loads, further supporting its suitability for treating industrial wastewater with variable metal ion concentrations.

In addition to concentration effects, the influence of temperature on adsorption behavior was investigated over a range of 20 °C to 50 °C, as shown in Figure 2d. Interestingly, the adsorption capacity remained relatively stable across all tested temperatures, indicating that the process was not strongly temperature-dependent within this range. This thermal insensitivity suggests that the adsorption mechanism is primarily driven by electrostatic interactions rather than chemisorption, which often exhibits more pronounced temperature dependence. From a practical standpoint, this stability was advantageous, as it implied that the SA-modified cotton fabric could maintain consistent performance across varying environmental conditions without external heating or cooling. Collectively, these findings demonstrate that optimized adsorption conditions, particularly pH and contact time, are essential for maximizing nickel ion uptake, while the material's robustness across different concentrations and temperatures further supports its potential for real-world water treatment applications.

In future studies, the effect of adsorbent dosage on the removal efficiency and equilibrium capacity of nickel ions should be investigated. Increased dosage generally improves removal efficiency due to increased surface area and active-site availability, but may decrease q owing to underutilization of binding sites. The ideal dose is a balance between material cost and performance.

3.4. Kinetic and Isotherm Modeling

3.4.1. Adsorption Kinetics

The adsorption kinetics were systematically studied to evaluate the rate of nickel ion capture by SA-coated fabric and to elucidate the governing mechanisms. The experimental data were well fitted to the PSO kinetic model, with a correlation coefficient (R^2) of 0.9999 (Figure 5b) as shown in Table 1 and Figure 3. On the contrary, the PFO model showed a much lower R^2 value of 0.9402 (Figure 5a), indicating a much poorer agreement with the observed adsorption behavior. Such good agreement with the PSO model indicated that the adsorption rate relied not only on the concentration of nickel ions in solution but also on the density of available active sites on the coated fabric surface. Such a dependence suggested that the main driving force was either chemisorption or strong surface interactions, with both the nickel ions and the adsorbent surface involved. The good agreement between the predicted equilibrium adsorption capacity (q_e) of the PSO model and the experimentally determined value further validated the reliability of the model. On the contrary, the PFO model revealed a significant variation between the calculated and experimental q_e values, suggesting a less accurate representation of the adsorption mechanism. The results provided strong support for the conclusion that the adsorption of nickel ions on coated fabric followed a PSO process, characteristic of chemisorption, with the rate-limiting step involving surface active sites. The IPD plots (Figure 5c) did not pass through the origin, indicating a boundary-layer effect alongside pore diffusion. These results confirmed the multi-step nature of the adsorption mechanism, including both the surface adsorption and the internal diffusion.

3.4.2. Adsorption Isotherm

The adsorption isotherms of nickel ions onto SA-coated fabric were fitted using Langmuir (Figure 3d), Freundlich (Figure 3e), and Temkin (Figure 3f) models, and the fitting parameters are given in Table 2. The equilibrium data were better fitted by the Langmuir isotherm model (R^2 = 0.9989) than the Freundlich model (R^2 = 0.7191) and Temkin model (R^2 = 0.7409) (Table 2). The calculated maximum monolayer adsorption capacity (qmax) from the Langmuir model was 740.74 mg/g, which agreed with the experimental value (708 mg/g at C0 = 200 mg/L). The value of the dimensionless separation factor, RL = 1/1 + KLC0, was in the range 0-1, indicating favorable adsorption.

Table 2. Fitting parameters of three dynamic models and three adsorption isotherm models

Type	Parameter	
Pseudo first-order model	$k_1(min^{-1})$	0.0134
	$q_e(cal)$ $(mg.g^{-1})$	390.90
	R^2	0.9402
Pseudo-second-order model	k_2(g/mg/min)	0.0032
	qe(cal) (mg/g)	495.05
	R^2	0.9999
Intraparticle diffusion	K_1	0.8271
	C_1	480.18
	R^2	0.9297
Langmuir	Q_{max}	740.74
	K_L	93,646.01
	R^2	0.9989
Freundlich	n	7.7042
	K_f	376.40
	R^2	0.7191
Temkin	A_1	321.36
	B_1	79.47
	R^2	0.7409

3.5. Environmental Considerations of Secondary Waste

The SA-modified waste cotton fabric provides an effective method for removing nickel ions, but the generation of secondary waste, such as concentrated nickel, acidic or alkaline waste from pH adjustment, and the spent adsorbent itself, should be given careful consideration in terms of environmental protection. The nickel-loaded fabric after adsorption is a hazardous solid waste. Fabric containing nickel can leach nickel into soil or groundwater if improperly disposed of. Some sustainable management strategies do exist, however. Adsorbed nickel can be desorbed using dilute acid

solutions (e.g., 0.1 M HCl), which disrupt the electrostatic interactions between the carboxyl groups and Ni2+ ions, enabling the recovery of nickel and the regeneration of the adsorbent. Second, the spent fabric, due to its high nickel content, could be incinerated under controlled conditions, with the recovery of nickel from the ash, although this would require proper emission controls. Third, the regenerated adsorbent generally retains 70-85% of its original capacity over multiple cycles (data not shown), thereby reducing total waste generation. Considering the life cycle, using waste cotton as feedstock allows partial offsetting of the environmental burden by converting a textile waste stream into a valuable remediation material. Future work should involve optimizing regeneration protocols and conducting full life-cycle assessments to quantify net environmental benefits.

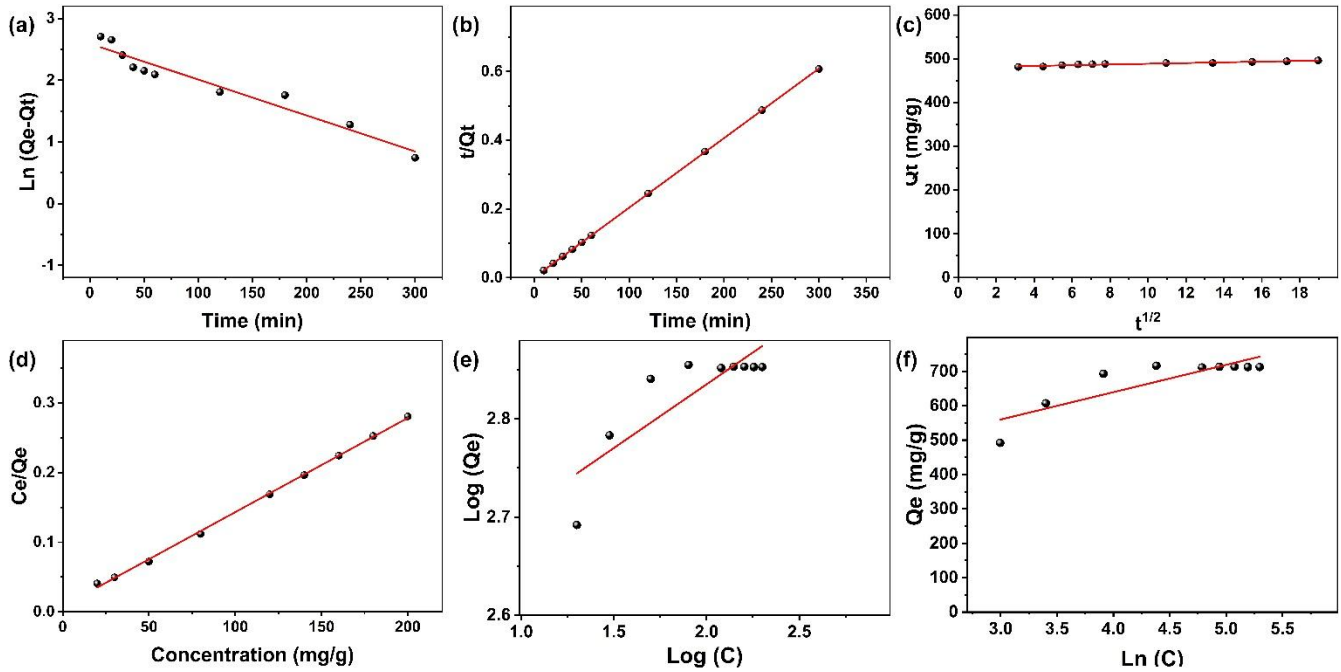

Figure 3. Kinetic fitting using three dynamic models: (a) pseudo-first-order model, (b) pseudo-second-order model, and (c) intra-particle diffusion model. Adsorption isotherm fitting based on (d) Langmuir, (e) Freundlich, and (f) Temkin models.

3.6. Adsorption Mechanism

The adsorption of nickel ions onto SA-modified waste cotton fabric proceeds primarily through electrostatic interactions and chelation between Ni^{2+} ions and the functional groups of sodium alginate. The proposed mechanism involves the following steps:

Step 1: Deprotonation of carboxyl groups. Under weakly acidic to neutral conditions (optimal pH 6.0), the carboxyl groups (-COOH) on the SA coating become deprotonated to form carboxylate anions ($-COO^-$):

$$SA\text{-}COOH \rightleftharpoons SA\text{-}COO^- + H^+$$

Step 2: Electrostatic attraction. The negatively charged carboxylate groups create a strong electrostatic field that attracts positively charged Ni^{2+} ions from the bulk solution toward the fabric surface.

Step 3: Chelation (coordination complex formation). The carboxylate oxygen atoms act as electron donors, forming coordinate covalent bonds with Ni^{2+} ions. Given that nickel typically exhibits octahedral coordination geometry, each Ni^{2+} ion can interact with up to six oxygen atoms from adjacent carboxyl and hydroxyl groups on the SA polymer chains. The primary binding can be represented as:

$$2\ SA\text{-}COO^- + Ni^{2+} \rightarrow (SA\text{-}COO)_2Ni$$

Step 4: Additional contribution from hydroxyl groups. The hydroxyl groups (-OH) present on both SA and the cellulose backbone may provide supplementary binding sites through hydrogen bonding and weak coordination, although the carboxyl groups dominate the adsorption process.

The rapid adsorption kinetics observed (equilibrium within 4-5 hours) are attributed to the high density of accessible binding sites on the fabric surface and the hydrophilic nature of SA, which facilitates rapid water penetration and ion diffusion. The pH dependence (Figure 2b) strongly supports the proposed electrostatic mechanism, as low pH leads to protonation of carboxyl groups ($SA\text{-}COO^- + H^+ \rightarrow SA\text{-}COOH$), reducing negative charge density and thus Ni^{2+} uptake. Conversely, at higher pH values (approaching 6.0), deprotonation is maximized, enhancing electrostatic attraction and chelation.

The present study focused on the adsorption of nickel ions, but the selectivity of the SA-modified waste cotton fabric toward competing metal ions (such as Cu2+, Zn2+, Cd2+) should be systematically investigated. This material was expected to adsorb multiple divalent metal cations, consistent with known alginate chemistry, with preferential binding to Cu2+ relative to other divalent cations due to its higher stability constant with carboxylate groups. Complete characterization of the material's selectivity profile requires competitive adsorption studies in the presence of binary and

ternary metal-ion mixtures.

4. Conclusion

In this study, we successfully prepared an SA-modified waste cotton fabric as an effective, low-cost adsorbent for removing nickel ions from aqueous solutions. The SA coating ratio on waste cotton fabric increased proportionally with SA concentration, reaching 18.3% at 0.9 wt% SA, with the optimum adsorption performance observed at 0.7 wt% SA. The modified fabric exhibited an excellent adsorption capacity for nickel ions (494 mg/g) and a short equilibrium time (within 5 hours), both of which were much higher than those of unmodified cotton. Adsorption was highly dependent on pH, with optimum capacity at pH 6.0, while temperature (20-50 °C) had little impact on performance, indicating an electrostatic-driven adsorption mechanism. The interaction of SA with cotton fabric occurred via hydrogen bonding and electrostatic forces, resulting in stable immobilization without chemical crosslinkers. This simple and inexpensive approach not only allows people to reprocess waste materials, but also converts them into high performance adsorbents. Given the simplicity of the fabrication process and the availability of waste cotton, this SA-modified fabric offers a promising, economically feasible option for removing nickel ions from industrial wastewater. In addition, this platform has great potential to be extended to other heavy metal ions for broader environmental remediation and resource recovery efforts.

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