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CADMIUM REMOVAL FROM THE WASTEWATER USING A CHEMICALLY ALTERED HYDROGEL FROM PLANT SEED MUCILAGE

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Abstract
Cadmium (Cd(II)) is a highly toxic heavy metal frequently detected in industrial wastewater and poses serious risks to human health and aquatic ecosystems. In this study, a chemically altered hydrogel derived from plant seed mucilage was synthesized as an eco-friendly and cost-effective adsorbent for Cd(II) removal from aqueous solutions. The hydrogel was chemically modified to enhance the availability of active functional groups and improve its adsorption performance. The prepared material was characterized using standard analytical techniques to confirm its structural and physicochemical properties. Batch adsorption experiments were conducted to investigate the effects of solution pH, contact time, adsorbent dosage, initial Cd(II) concentration, and temperature. The modified hydrogel exhibited high adsorption efficiency due to the synergistic contribution of ion exchange, electrostatic attraction, and surface complexation mechanisms. The adsorbent also demonstrated satisfactory regeneration and reusability over multiple adsorption–desorption cycles. These findings highlight that the chemically altered plant seed mucilage hydrogel is a sustainable, low-cost, and efficient adsorbent with significant potential for the treatment of cadmium-contaminated wastewater.

1. Introduction

The rapid growth of industrialization and urbanization has significantly increased the discharge of toxic heavy metals into aquatic ecosystems, posing a major threat to environmental sustainability and public health. Among these contaminants, cadmium (Cd^{2+}) is considered one of the most hazardous due to its high toxicity, non-biodegradable nature, long biological half-life, and tendency to accumulate in living organisms through the food chain. Cadmium is commonly released into wastewater from electroplating, battery manufacturing, mining, pigments, fertilizers, metal finishing, and textile industries. Even at trace concentrations, prolonged exposure to cadmium can lead to severe health disorders, including renal dysfunction, bone demineralization, liver damage, and carcinogenic effects. Consequently, the World Health Organization (WHO) has established a maximum permissible concentration of **0.003 mg L^{-1}** for cadmium in drinking water, highlighting the urgent need for efficient and sustainable treatment technologies for cadmium-contaminated wastewater [1].

Several conventional methods have been employed for cadmium removal, including chemical precipitation, ion exchange, membrane filtration, electrochemical treatment, and solvent extraction. Although these techniques can achieve satisfactory removal efficiencies under specific conditions, they often suffer from high operational costs, excessive chemical consumption, generation of secondary sludge, membrane fouling, and reduced effectiveness at low metal concentrations. In recent years, adsorption has emerged as one of the most promising alternatives owing to its simplicity, cost-effectiveness, high efficiency, ease of operation, and potential for adsorbent regeneration [2-12]. The performance of adsorption systems largely depends on the physicochemical properties of the adsorbent, particularly the availability of active binding sites capable of interacting with heavy metal ions [13-15].

Natural polymers have gained considerable attention as environmentally benign adsorbent materials because they are renewable, biodegradable, non-toxic, and rich in functional groups such as hydroxyl, carboxyl, and amino moieties that facilitate metal-ion complexation. Among these materials, plant seed mucilage represents an attractive yet underexplored biomass resource. Plant seed mucilage is a naturally occurring heteropolysaccharide composed primarily of arabinose, galactose, rhamnose, xylose, mannose, uronic acids, and other sugar residues. Owing to its hydrophilic nature and abundant reactive functional groups, seed mucilage exhibits excellent water absorption, gel-forming ability, and biocompatibility, making it an ideal precursor for developing advanced adsorbent materials. However, the adsorption capacity of native mucilage is generally limited by its poor mechanical stability, low surface area, and insufficient density of metal-binding sites [16-28].

Chemical modification has proven to be an effective strategy for overcoming these limitations by introducing additional functional groups and improving the structural integrity of natural polysaccharides. Grafting synthetic monomers, crosslinking polymer chains, and incorporating ionizable functional groups significantly enhance the swelling behavior, porosity, stability, and adsorption performance of plant-derived hydrogels. In particular, chemically altered hydrogels containing abundant carboxyl and hydroxyl group's exhibit strong affinity toward divalent metal ions through ion exchange, electrostatic attraction, surface complexation, and chelation mechanisms. Their three-dimensional crosslinked network provides numerous accessible adsorption sites while maintaining structural stability during repeated adsorption–desorption cycles, making them attractive candidates for wastewater treatment applications [30, 31].

Hydrogels synthesized from plant seed mucilage combine the environmental advantages of natural biopolymers with the enhanced functionality imparted by chemical modification. Such hydrogels possess high swelling capacity, interconnected porous morphology, and tunable physicochemical properties that facilitate rapid diffusion and efficient sequestration of heavy metal ions from aqueous media. Furthermore, the use of renewable plant-derived materials aligns with the principles of green chemistry and sustainable resource utilization, reducing dependence on petroleum-based synthetic adsorbents while minimizing environmental impacts associated with material production and disposal [32].

In this study, a chemically altered hydrogel was developed from plant seed mucilage and evaluated as an efficient adsorbent for the removal of cadmium ions from wastewater. The hydrogel was synthesized through chemical modification to improve its adsorption performance by increasing the density of active functional groups and enhancing its structural stability. The prepared material was comprehensively characterized using physicochemical techniques, while its adsorption behavior toward Cd^{2+} was investigated under various experimental conditions. The adsorption mechanism was further elucidated based on kinetic, isotherm, thermodynamic, and spectroscopic analyses to assess the potential of the chemically modified plant seed mucilage hydrogel as a sustainable and high-performance adsorbent for heavy metal remediation.

2. METHODOLOGY

2.1. Materials

Linum usitatissimum locally procured was chosen as raw material for the present investigation. The seeds were cleaned by screening to remove dust, dirt and other impurities from the seeds prior to further processing. Analytical grade reagents were used in all experiments. All the solutions and experimental preparations were carried out in deionized water (DW).

2.2. Extraction of Flaxseed Hydrogel

The extraction of flaxseed hydrogel is done using an aqueous extraction method adapted from that reported by the same group. The seeds were soaked in distilled water for 3 h to improve the water uptake. Seeds were then soaked and kept at 50 °C for 30 min to encourage the release of mucilage. This gel-like material was then squeezed through cotton cloth with the help of a spatula to remove the seed mass. To remove the non-polar impurities and to increase the purity of the recovered hydrogel, it was treated with n-hexane. The material was then purified and dried and stored in a sealed container for further experimentation.

2.3. Preparation of Copolymer Hydrogel

Linseed mucilage 1.0 g was dispersed in 50 mL of DW and shaken continuously at 60 °C for 2 h to get uniform viscous dispersion. Then, the reaction medium was gradually changed to contain methacrylic acid and the initiator and crosslinking agent were added. The polymerization was carried out at 70 °C for 24 h to form a copolymer hydrogel network. At the end of reaction, ethanol was added to precipitate the hydrogel. The product obtained was washed several times with washing solvents to remove the remaining monomer and unreacted materials. Finally, after purification, the hydrogel was dried at 50 °C, ground up to fine powder and stored under dry conditions for further use.

2.4. Batch Cd(II) Adsorption Studies

The adsorption of Cd(II) onto the material was thus examined batch experiments. The batch experiments were conducted to explore the adsorption performance of copolymer hydrogel to Cd(II) ions. The influence of the operational variables like solution pH, concentration of metal ions, dosage of adsorbent, contact time and contact temperature on the process was systematically investigated. $Cd(NO_3)_2{\cdot}4H_2O$ was used to prepare stock solution of Cd(II) and then further diluted to obtain the required concentrations. In each experiment the volume of Cd(II) solution was measured and transferred into a conical flask and the required pH was adjusted. Then a fixed amount of hydrogel was added to the solution. Contact time was maintained by shaking the mixtures for the desired duration under controlled conditions. The hydrogel was then separated from the solution and the concentration of remaining Cd(II) in the solution was determined using flame atomic absorption spectroscopy at 228.8 nm.

$$q_e = \frac{C_i - C_e}{m} \times V \qquad (1)$$

$$\text{Cd(II) adsorption capacity (\%)} = \frac{C_i - C_e}{C_i} \times 100 \qquad (2)$$

The difference between initial concentration and equilibrium concentration of Cd(II) ions gave the adsorption capacity and removal efficiency.

3. Results and discussion

3.1. Effect of pH

The adsorption properties of synthesized copolymer hydrogel were studied at different pH levels to evaluate consequence of solution acidity on retention of adsorbate. The obtained consequences revealed that retention was relatively low in strongly acidic media, especially below pH 3. Under such conditions, functional assemblies existing in hydrogel assembly remained well connected with hydrogen ions, limiting their protagonist in the retention process. A significant increase in retention capacity was experimental with improvement in pH of the medium [15]. This improvement was more significant in the pH range of 4-6, in which number of adsorption dynamic positions on the hydrogel surface improved (Fig. 1). Hence, stronger interaction between hydrogel matrix and adsorbate species occurred, leading to better adsorption performance. The extreme retention capacity became pragmatic at pH 6, which means that this pH was the most suitable for adsorbate uptake. Above this pH value, adsorption capacity reduced with swelling pH. This decrease is due to changes in physicochemical characteristics of the adsorption system, which reduced the effectiveness of interactions between the adsorbate molecules and the hydrogel network. These results suggest that aqueous medium pH is a major issue regulatory the retention efficiency of the prepared hydrogel and pH 6 is the optimum condition for adsorption.

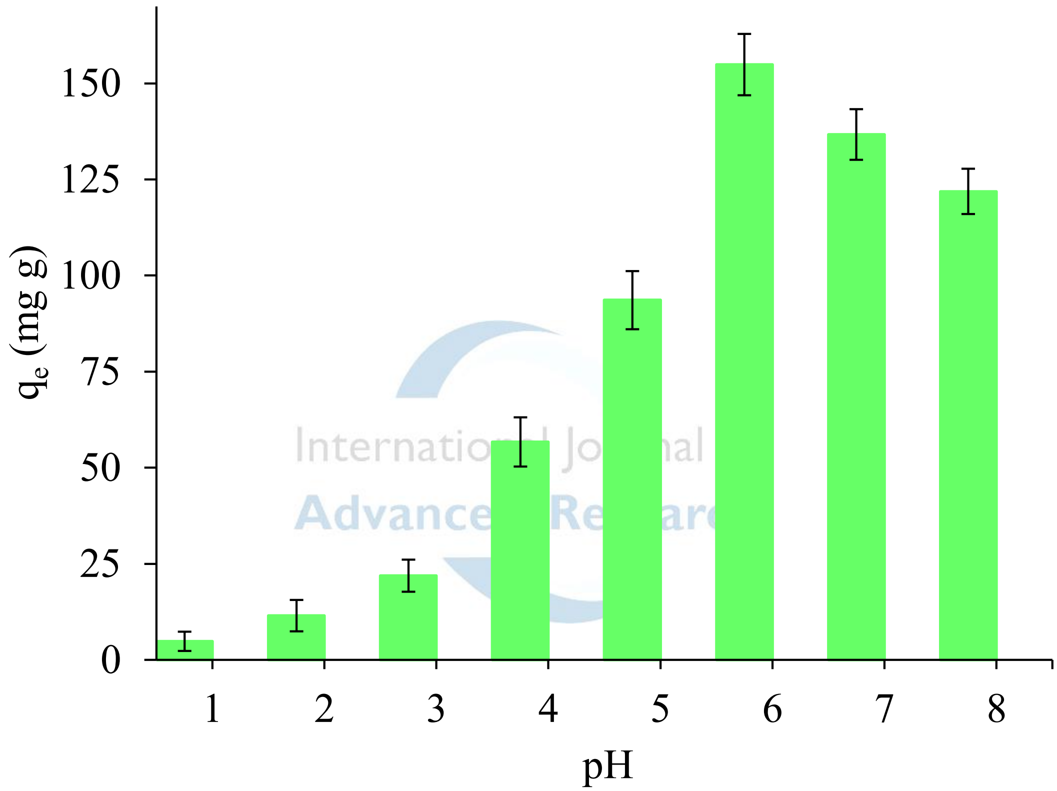

Fig. 1. Effect of pH

3.2. Effect of Initial Concentration

The variations in initial concentration of Cd(II) greatly affected adsorption behaviour of the synthesised hydrogel. The amount of adsorbate held by the hydrogel increased in the whole investigated concentration range, from almost 25 mg g^{-1} to approximately 150 mg g^{-1}. At intermediate concentrations a more pronounced increase was observed, while at higher concentrations the curve gradually flattened (Fig. 2). This trend indicates that initially the hydrogel was rich in available adsorption sites for adsorbate binding. With further increase in concentration these sites were progressively occupied, that left less possibility for further uptake. Consequently, the variation in adsorption capacity was observed to be less at higher concentration levels [23]. The almost horizontal portion of the curve reflects the limited availability of unoccupied sites in the hydrogel network and points to the adsorption system reaching its maximum retention capability under the given conditions.

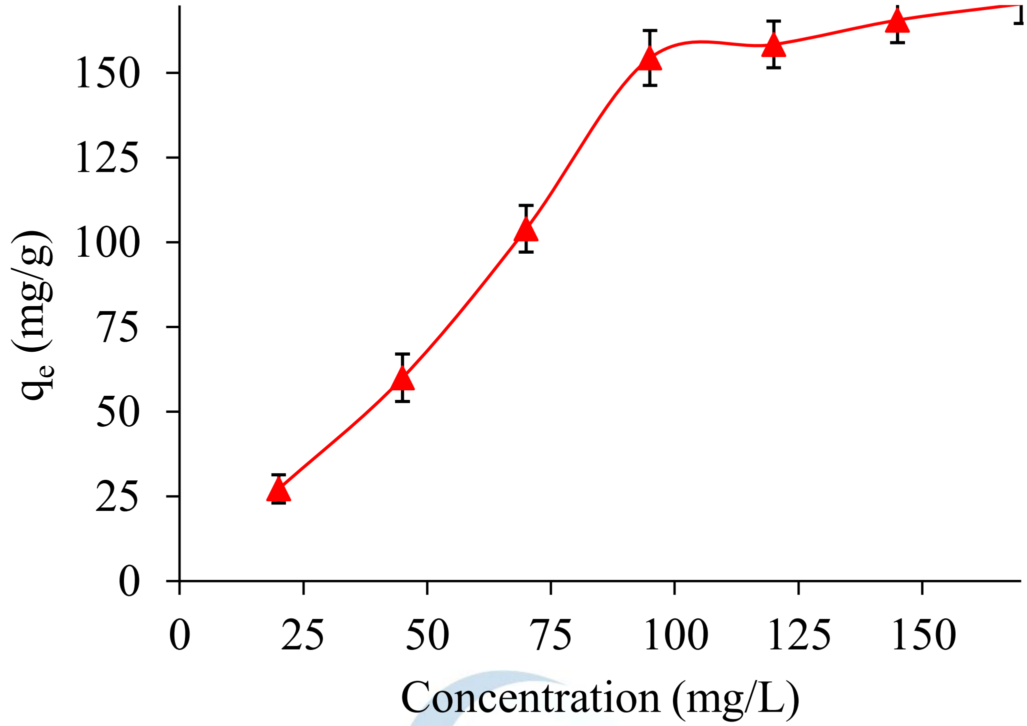

Fig. 2. Effect of concentration

3.3. Effect of contact time

The adsorption performance of synthesized hydrogel was explored to study the influence of contact period for 5-60 min. The resolution of this investigation was to assess hydrogel's adsorption assets and gather data on retention process' kinetics. The high adsorption value was recorded at 35 min of contact between the adsorbent and adsorbate, showing that retention volume of the adsorbent rises as contact time increases (Fig. 3). Based on data of the experiment retention occurred rapidly in the initial part of the experiment and touched stable condition 35 min. After this time retention system is considered to be at equilibrium conditions, with very little change in adsorption capacity [11]. The fast absorption at the beginning of process is due to high percentage of unoccupied active places on interface of hydrogel. The number of unoccupied binding sites decreased steadily as adsorption progressed and these sites were gradually occupied. Thus, rate of retention slowly decreased up to equilibrium was grasped when further adsorption was prevented because the adsorption sites were filled.

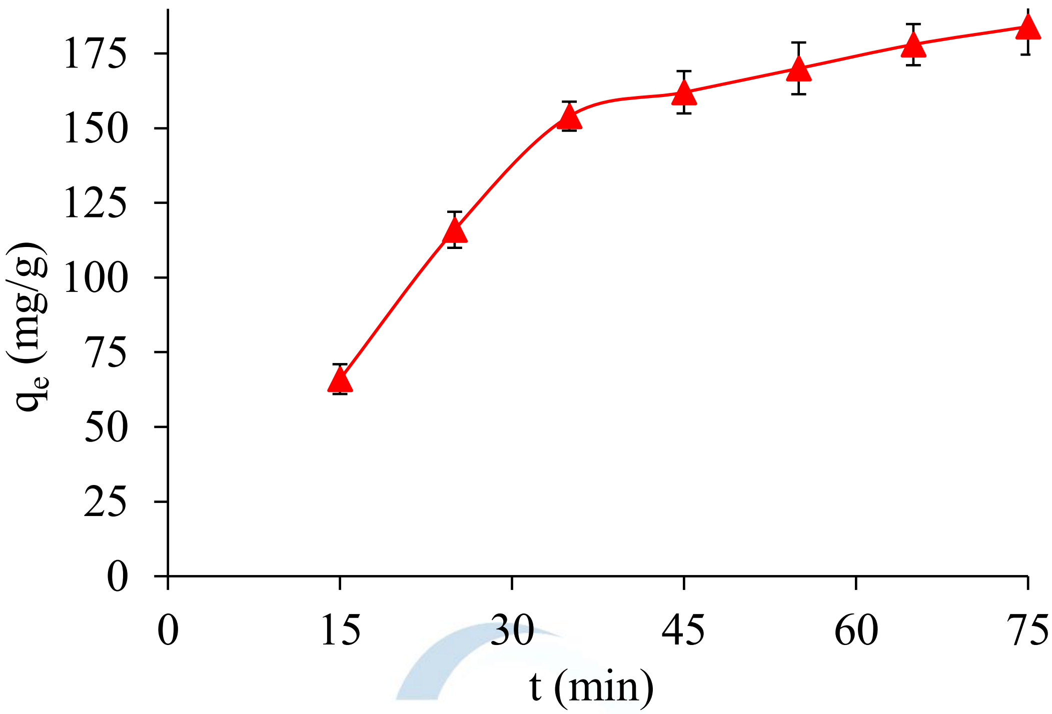

Fig. 3. Effect of time

3.4. Effect of Dose

The effect of the amount of the absorbents on the adsorption behaviour of the synthesised hydrogel was investigated by increasing the amount of the hydrogel from 10 to 90 mg and all other experimental parameters were kept unchanged. The increasing adsorption capacity with the inclusion of the hydrogel was found. This improvement is due to a rise in number of active required positions in system and a rise in the area for adsorption. Dosage of 25 mg of hydrogel exhibited high adsorption capacity among dosages tested (Fig. 4). This result was then used to choose an optimum adsorbent concentration for all further adsorption studies, which was 25 mg. In the case of higher than optimum dose of the hydrogel, there was adsorption reduction observed. Higher concentrations of this behavior might be related to aggregation or clustering of the hydrogel particles, which may reduce the available surface area for the adsorbate [18]. This means that some of the adsorption sites become less available, decreasing the overall adsorption efficiency of the hydrogel system.

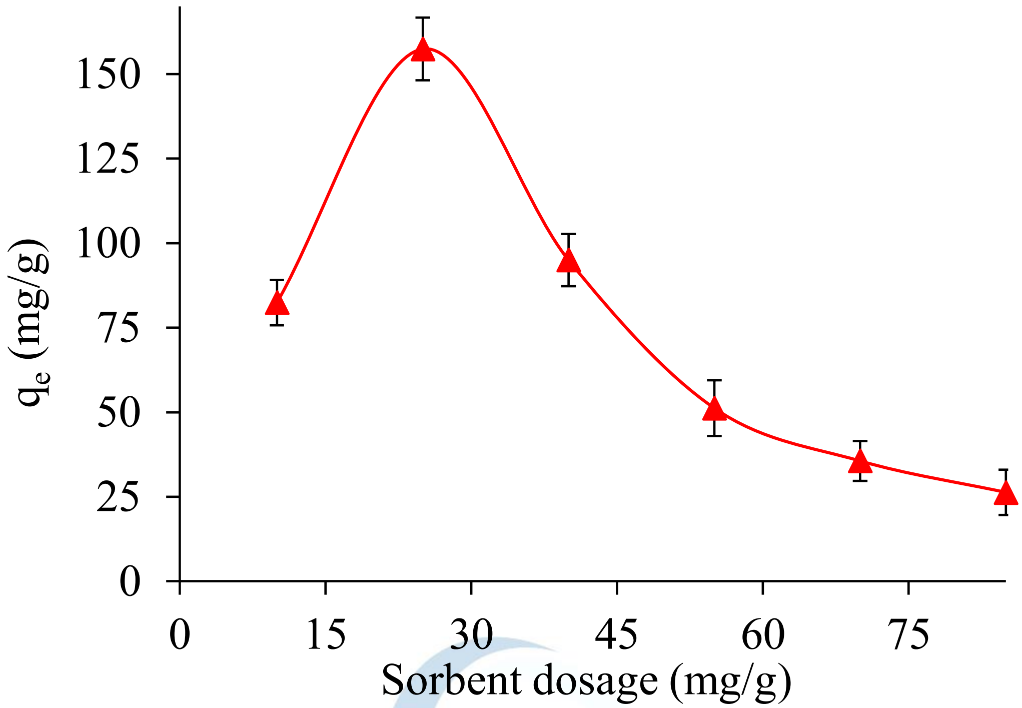

Fig. 4. Effect of dose

3.5. Effect of temperature

Effect of temperature on adsorption behavior of synthesized hydrogel was investigated in the temperature range of 298–338K, and relevant thermodynamic parameters were determined. With rising temperature, a steady reduction in retention capacity was detected. The maximum adsorption capacity was resolute at 298 K, indicating that lower temperatures favoured retention process (Fig. 5). The observed reduction in effectiveness of adsorption with growing temperature recommends that the interaction between the adsorbing species and hydrogel interface became less favourable at higher temperatures. The rise of the adsorption at lower temperature is explained with the higher attractive interactions established between the molecules of adsorbing specie and the available functional assemblies of the hydrogel [23]. In contrast, the mobility of the adsorbate species in solution increased with temperature, which weakened their contact with the active adsorption sites. Therefore, the adsorption performance decreased as the temperature increased.

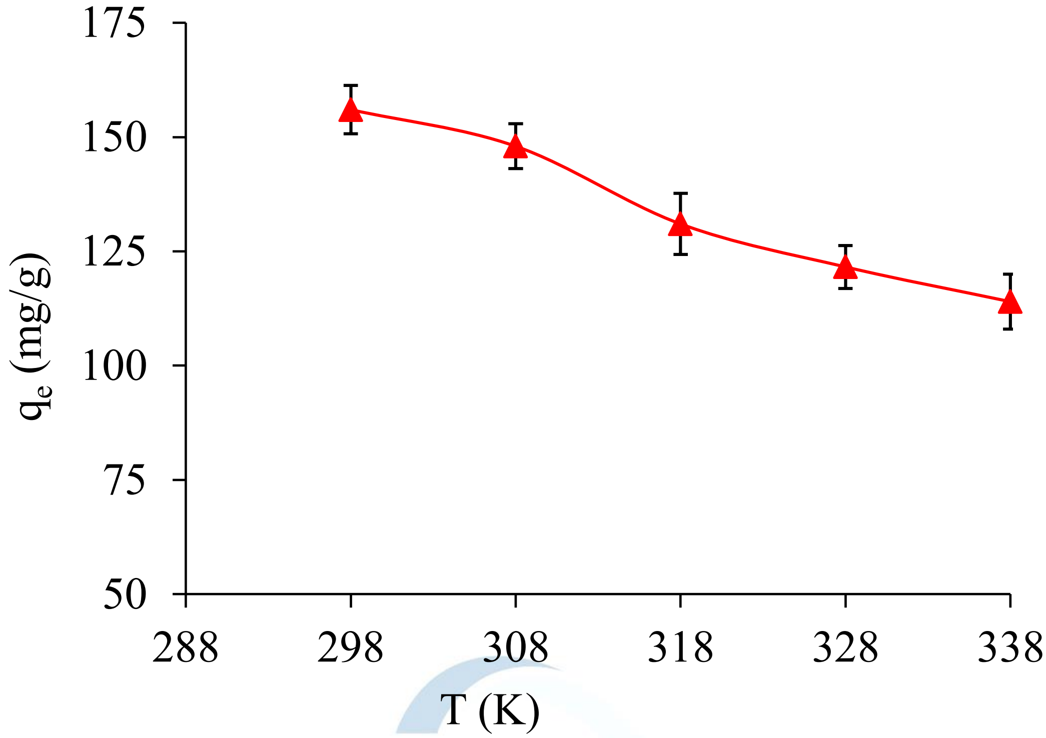

Fig. 5. Effect of temperature

4. CONCLUSIONS

A chemically altered hydrogel derived from plant seed mucilage was successfully developed and evaluated as an efficient adsorbent for the removal of Cd(II) ions from wastewater. Chemical modification enhanced the availability of functional groups, resulting in improved adsorption performance and greater affinity toward cadmium ions. Batch adsorption studies demonstrated that Cd(II) removal was significantly influenced by solution pH, contact time, adsorbent dosage, initial metal ion concentration, and temperature. The adsorption process showed favorable agreement with appropriate isotherm and kinetic models, indicating efficient interaction between the hydrogel and Cd(II) ions. The adsorption mechanism was primarily governed by electrostatic attraction, ion exchange, and complexation between Cd(II) ions and the functional groups present on the hydrogel surface. Furthermore, the adsorbent exhibited good regeneration ability and maintained satisfactory adsorption efficiency over repeated adsorption–desorption cycles, confirming its reusability and stability. Owing to its biodegradability, low cost, environmental compatibility, and high adsorption efficiency, the chemically altered plant seed mucilage hydrogel represents a promising and sustainable material for the treatment of cadmium-contaminated wastewater. Future studies should focus on evaluating its performance in real industrial wastewater, investigating competitive adsorption in multi-metal systems, and assessing its large-scale application for practical water purification.

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