COMPARATIVE ION EXCHANGE PERFORMANCE OF IMINODIACETATE AND AMINOPHOSPHONATE RESINS FOR EFFICIENT CADMIUM REMOVAL FROM AQUEOUS SOLUTIONS

HÜMA ÖZCAN [1], ÖZGÜR ARAR [1,], AND MÜŞERREF ARDA[1]*

[1]*Chemistry Department of Ege University, Izmir, Türkiye.*

ABSTRACT

The removal of cadmium ions (Cd^{2+}) from aqueous media was systematically investigated using two commercial chelating ion-exchange resins: Puromet MTS9300, functionalized with iminodiacetic acid groups, and Puromet MTS9500, containing aminophosphonic acid groups. The effects of resin dosage, solution pH, temperature, and contact time on Cd^{2+} removal were evaluated through batch experiments. The results revealed that both resins exhibited high Cd^{2+} removal efficiencies, achieving complete removal under optimized conditions. Ion exchange performance was strongly influenced by solution pH, as both resins possess weakly acidic functional groups that undergo protonation in acidic media, thereby reducing Cd^{2+} uptake. Kinetic data fitted well to the pseudo-second-order model. The equilibrium data correlated closely with the Langmuir model, with maximum exchange capacities of 201.33 mg/g for MTS9300 and 191.44 mg/g for MTS9500 at 30 °C. Thermodynamic analysis confirmed the spontaneous nature of Cd^{2+} removal for both resins, with $\Delta G°$ values ranging from –26.37 to –30.09 kJ/mol. MTS9500 exhibited an endothermic exchange process, while MTS9300 displayed exothermic behaviour. Regeneration experiments demonstrated excellent reusability with both HCl and H_2SO_4 solutions, maintaining nearly 100% regeneration efficiency. These findings highlight the high potential of MTS9300 and MTS9500 resins as efficient, regenerable materials for the removal of cadmium ions from contaminated water.

Keywords: Cadmium removal; Chelating ion exchange resin; Iminodiacetic acid; Aminophosphonic acid; Regeneration.

1. INTRODUCTION

Cadmium is a highly toxic heavy metal pollutant of global environmental and public health concern, owing to its non-biodegradable nature and strong bioaccumulation potential in living organisms [1]. It is commonly introduced into aquatic environments through anthropogenic activities such as battery manufacturing, electroplating, mining, agricultural runoff, and sewage sludge application [2–4]. Although cadmium is industrially valuable in batteries and pigments, its environmental persistence and accumulation in the food chain pose severe ecological and health risks [1,5].

Once absorbed by living organisms, cadmium disrupts enzymatic activity and causes significant organ dysfunction, particularly in the kidneys, lungs, and reproductive system [6]. It is a non-essential element with no known biological role, and the World Health Organization limits its concentration in drinking water to 3 µg/L [7]. Beyond human exposure, cadmium contamination impairs plant growth, decreases crop productivity, and accumulates in animal tissues, subsequently transferring through the food chain [8]. Owing to its persistence, solubility, and carcinogenicity, the removal of cadmium from industrial effluents prior to discharge is essential [9].

A range of physicochemical and biological methods have been applied for Cd^{2+} removal from aqueous media. Among conventional techniques, chemical precipitation remains widely used due to its simplicity and low cost, involving the formation of insoluble $Cd(OH)_2$ or CdS precipitates. Adsorption is another efficient method, transferring metal ions from the aqueous phase to solid surfaces via physicochemical interactions [10–12]. Numerous adsorbents—including mineral clays, agricultural wastes, and activated carbon—have been evaluated, and adsorption is favored for its simplicity, high efficiency, and cost-effectiveness [13,14]. Ion exchange processes are also extensively employed, in which Cd^{2+} ions are replaced by other ions bound to an insoluble matrix, using materials such as Purolite resins, zeolites, or fly ash [10,11]. Membrane separation processes, including reverse osmosis, nanofiltration, and ultrafiltration, achieve high cadmium removal efficiencies. However, membrane fouling and limited durability under variable conditions restrict their large-scale application. Solvent extraction provides an alternative for the selective recovery of metal ions from concentrated. In parallel, biological methods, such as bioremediation and biosorption, employ microorganisms, fungi, seaweeds, and agricultural residues to remove Cd^{2+} in an environmentally benign manner. Despite their diversity, most of these techniques face challenges including high operational cost, complex regeneration, and reduced efficiency at low metal concentrations [10–12,15].

Recent studies have focused on developing sustainable sorbents and nanostructured materials for cadmium remediation. Mahmoud et al. synthesized green copper oxide nanoparticles that achieved an 18 % Cd removal efficiency at pH 6, with a maximum adsorption capacity (q_m) of 15.60 mg/g at 0.33 g/L sorbent dose. Adsorption followed pseudo-second-order kinetics, reached equilibrium within 60 min, and conformed to the Freundlich isotherm, indicating a heterogeneous adsorption surface [16] . Kayranlı (2021) investigated cadmium adsorption using recycled lignocellulosic biomass from pistachio, peanut, and almond shells, where removal occurred via electrostatic interaction, ion exchange, complexation, and physical adsorption. The maximum adsorption capacities ($q_{e,max}$) were 51.28 mg/g for pistachio, 62.11 mg/g for peanut, and 78.74 mg/g for almond at pH 5. Adsorption kinetics followed the pseudo-second-order model, and equilibrium data fitted the Langmuir isotherm [17].

Abdel-Ghani et al. (2008) reported the use of *Eucalyptus camaldulensis* leaves for cadmium removal from synthetic wastewater, achieving 45 % efficiency at equilibrium. Maximum adsorption occurred within a pH range of 4.5–6.5, equilibrium was reached after 120 min, and the Temkin isotherm provided the best fit [18].

Among available technologies, ion exchange resins stand out for their efficiency and operational versatility in removing heavy metals such as cadmium. They offer advantages including high selectivity, efficient metal recovery, minimal sludge generation, and compliance with stringent discharge standards [19,20]. The process is characterized by rapid kinetics, high capacity, and suitability for a wide concentration range of metal ions. Ion exchange can eliminate most cationic and anionic pollutants, making it a reliable approach for large-scale wastewater treatment [15]. Moreover, the method is easy to operate and maintain, providing precise control over treatment parameters [13]. When utilized as catalyst supports, ion exchange resins further offer advantages of recyclability, reproducibility, and straightforward characterization [21].

Building upon this framework, the present study investigates the performance of two commercial chelating ion exchange resins, Purolite MTS9300 and Purolite MTS9500, functionalized with iminodiacetic acid (IDA) and aminophosphonic acid groups, respectively, for the efficient removal of Cd^{2+} ions from aqueous solutions. These resins are specifically designed to provide high selectivity toward divalent metal cations through coordinated ion exchange mechanisms. Comprehensive experiments were performed to evaluate the influence of key operational parameters, including solution pH, resin dosage, contact time, and temperature, on Cd^{2+} exchange performance. Kinetic and thermodynamic analyses were conducted to elucidate the controlling mechanisms and the nature of the ion exchange process. Furthermore, regeneration studies were carried out to assess the operational stability and economic feasibility of the resins. This work provides a comparative evaluation of IDA- and aminophosphonic-functionalized chelating resins and offers valuable insights into their potential application in the sustainable treatment of cadmium-contaminated waters.

**Corresponding author email: ozgur.arar@ege.edu.tr*

2. EXPERIMENTAL

2.1. Materials and reagents

Two commercial chelating cation-exchange resins—Purolite MTS9500 and Purolite MTS9300—were obtained from Purolite (Türkiye). The MTS9500 resin contains aminophosphonate functional groups, whereas the MTS9300 resin is functionalized with iminodiacetate groups. Cadmium sulfate octahydrate ($3CdSO_4 \cdot 8H_2O$, Merck) was dissolved in deionized water to prepare Cd(II) ion solutions used in batch ion exchange experiments. Ammonia (NH_3, Sigma-Aldrich) and sulfuric acid (H_2SO_4, Carlo Erba) hydrochloric acid (HCl, Carlo Erba) and sodium chloride (NaCl, Merck) solutions were utilized. For resin regeneration studies, hydrochloric acid (HCl, Carlo Erba) and sodium chloride (NaCl, Merck) solutions were utilized. The physical and chemical properties of Purolite MTS9300 and Purolite MTS9500 resins, as provided by the manufacturer, are summarized in Table 1.

Table 1. Physico-chemical properties of resins

Properties	MTS9300	MTS9500
Functional group	Iminodiacetic	Aminophosphonic
Matrix	Polystyrene crosslinked with divinylbenzene	Polystyrene crosslinked with divinylbenzene
Polymer structure	Macroporous	Macroporous
Moisture retention	52% - 60% (Na^+ form)	60% - 68% (Na^+ form)
Reversible swelling, ($H^+ \rightarrow Na^+$ max)	35%	50%
Specific gravity	1.18	1.13
Temperature limit	80 °C (176,0 °F)	80 °C (176,0 °F)
Capacity	50 g-Cu/L (1.57 eq/L)	1.3 eq/L

2.2 Conditioning of the Ion-Exchange Resin

The Puromet MTS9500 and MTS9300 resins were conditioned prior to use to remove manufacturing impurities, activate their functional groups, and prevent possible experimental errors. A 100 mL portion of wet resin was placed in a 500 mL plastic container, and 250 mL of 2 M NaCl solution was added. The mixture was shaken at 25 °C for 24 h, then filtered and washed thoroughly with deionized water. The resins were dried in an oven at 50 °C until constant weight was achieved. Particle size analysis was then performed, and resin particles within the 500–750 µm range were selected for the experiments.

2.3 Analyses

Metal ion concentrations were determined using a flame atomic absorption spectrometer (VARIAN SpectrAA 220). Analysis was performed with an acetylene-air mixture at a wavelength of 228.8 nm. Solution pH was determined using a Mettler Toledo FG2 pH Meter. The chelating ion-exchange resin was dried to a constant mass in a Heraous RT350 oven before use. Sorption equilibrium studies were conducted in a DLAB SK-O330-Pro Orbital Shaker. Kinetic experiments utilized a WiseBath water bath with a Biosan mechanical stirrer. Thermodynamic studies were performed in a Nüve ST402 shaking water bath.

2.4 Ion Exchange Studies

Batch ion exchange experiments were carried out using 25 mL Cd^{2+} solutions (5 mg/L) with varying amounts of Puromet MTS9300 and MTS9500 resins (0.025, 0.05, 0.1, and 0.2 g). The mixtures were agitated at 400 rpm for 24 h at 25 °C (room temperature). To evaluate Cd^{2+} removal efficiency and determine the pH Range, experiments were also performed at different pH values (1, 2, 3, 4, and 6) using 0.2 g of Puromet MTS9300 and 0.025 g of Puromet MTS9500 on an orbital shaker. After equilibration, the residual Cd^{2+} concentrations were measured by AAS

For the kinetic experiments, 1 g of Puromet MTS9500 resin was contacted with 1000 mL of 5 mg/L Cd^{2+} solution at pH 6, while 8 g of Puromet MTS9300 resin was contacted with 1000 mL of 5 mg/L Cd^{2+} solution under identical conditions. The mixtures were agitated in a thermostatic water bath at 30 °C and 400 rpm. At predetermined time intervals (0, 1, 3, 5, 15, 30, 60, 90, 120, 180, 240, 360, and 1440 min), 10 mL aliquots were withdrawn and analyzed for Cd^{2+} content.

Equilibrium ion exchange (isotherm) experiments were conducted using the optimum amounts of Puromet MTS9300 and MTS9500 resins with 25 mL Cd^{2+} solutions of varying concentrations (100–600 mg/L) at different temperatures (30, 40, and 50 °C). The samples were agitated in a shaking water bath at 400 rpm for 24 h to reach equilibrium. After equilibration, the resins were separated by filtration, and both initial and equilibrium Cd^{2+} concentrations were determined by (AAS).

All experiments were conducted in duplicate, and average values were used for data analysis and graphical representation. The equilibrium ion exchange capacity of the resin for Cd^{2+} (q_e, mg/g) was calculated using Equation (1), and the Cd^{2+} removal efficiency (R, %) was determined using Equation (2):

$$q = \frac{(C_0 - C_e) x\, V}{m} \; ......(1)$$

$$R(\%) = \frac{(C_0 - C_e)}{C_0} x\; 100 \; .... \; (2)$$

where C_0 and C_e are the initial and equilibrium Cd^{2+} concentrations (mg/L), V is the volume of solution (L), and m is the mass of the ion-exchange resin used (g).

3. RESULTS AND DISCUSSIONS.

3.1 Effect of resin dosage

The variation in Cd^{2+} removal efficiency as a function of resin dosage is presented in Figure 1. When the MTS9300 resin was employed, 88% removal was achieved at a resin dose of 0.025 g, increasing to 99% at 0.2 g. The increase in resin dosage enhanced the number of available active sites for Cd^{2+} ion exchange from the aqueous phase [22]. In contrast, the MTS9500 resin achieved nearly complete Cd^{2+} removal even at the lowest dosage (0.025 g), indicating its higher affinity for Cd^{2+} ions. The difference in ion-exchange performance between the two resins arises from their distinct functional groups: MTS9300 contains iminodiacetate groups that provide carboxylate donor sites, whereas MTS9500 contains aminophosphonate groups with hydroxyl functionalities that offer stronger chelating interactions with Cd^{2+} ions.

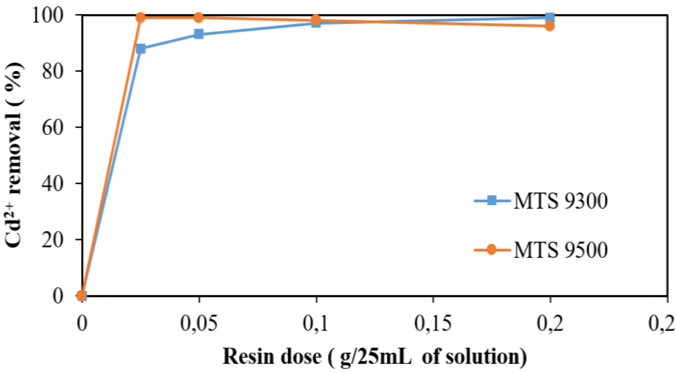

Figure 1. Effect of resin dosage on Cd^{2+} removal from aqueous solutions ([Cd^{2+}]: 5 mg/L, volume of solution 25 mL; pH: 6; shaking speed: 400 rpm; temperature: 25 ºC).

3.2 Effect of solution pH

The effect of initial solution pH on Cd^{2+}removal by Purolite MTS9500 and MTS9300 resins is illustrated in Figure 2. For both resins, Cd^{2+} removal efficiency increased markedly with increasing pH. When MTS9500 was used, only 26% of Cd^{2+} was removed at pH 1, whereas removal efficiency rose to 88% at pH 2 and reached nearly complete removal (≈99%) at pH 3 and above.

In contrast, the MTS9300 resin exhibited only 3% removal at pH 1 but achieved complete Cd^{2+} removal from pH 2 onward. Both resins possess weakly acidic functional groups that undergo protonation under strongly acidic conditions, converting into their molecular (non-ionized) forms and thereby reducing the number of active sites available for Cd^{2+} exchange. In the case of the iminodiacetate functional groups of MTS9300, both carboxylic groups and the nitrogen atom become protonated in solutions with pH values around 2 or lower, leading to diminished complexation ability toward Cd^{2+} ions [23]. As the pH increases, these groups progressively deprotonate, enhancing their capacity to coordinate Cd^{2+} through bidentate or tridentate complex formation. For the aminophosphonic acid functional groups of MTS9500, two bonding sites—one at the phosphonic acid group and one at the nitrogen atom—are available for coordination with Cd^{2+} ions [24].

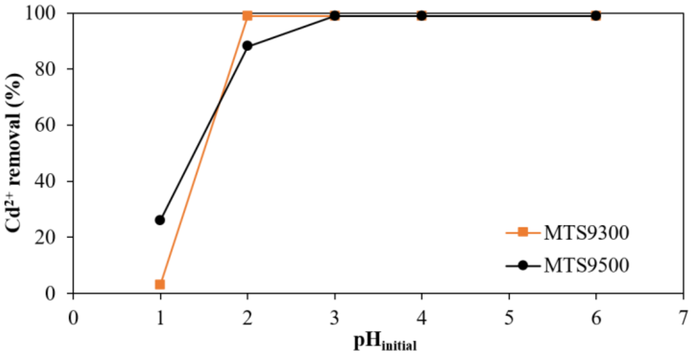

Figure 2. Effect of initial solution pH on Cd^{2+} removal ($[Cd^{2+}]$: 5 mg/L, volume of solution 25 mL; shaking speed: 400 rpm; temperature: 25 ºC, resin dosage MTS9300: 0.2 g; MTS9500: 0.025 g).

3.3 Contact time

The effect of contact time on Cd^{2+} removal by Purolite MTS9300 and MTS9500 resins is presented in Figure 3. For both resins, the ion-exchange rate increased rapidly during the initial contact period and gradually approached equilibrium as time progressed. In the case of MTS9300, approximately 74% of Cd^{2+} was exchanged within the first 15 minutes, and equilibrium was reached after 180 minutes with 94% removal, ultimately achieving complete removal (99%) after 24 hours. For MTS9500, the ion-exchange rate was slower at the early stages, with 28% removal after 15 minutes and 69% after 180 minutes, reaching equilibrium at 360 minutes. The faster kinetic behavior of MTS9300 may be associated with its higher ion-exchange capacity (1.57 eq/L) compared to MTS9500 (1.30 eq/L), which provides a greater number of active functional sites for Cd^{2+} uptake.

The kinetic data were analyzed using pseudo-first-order and pseudo-second-order models [25,26]. The fitting results (Table 2) demonstrated that the pseudo-second-order equation provided an adequate description of the experimental data within the studied range.

Table 2. Calculated kinetic parameters for Cd^{2+} sorption onto MTS9300 and MTS9500 resins

Kinetic model	Parameter	MTS9300	MTS9500
Pseudo-first-order	k_1 (min^{-1}) q_e (mg/g) R^2	0.0490 1.7719 0.8699	0.0062 2.5458 0.7710
Pseudo-second-order	k_2 (g/mg min) q_e (mg/g) h (mg/gmin) R^2	3.2575 0.0620 0.6582 0.9990	0.0003 13.6528 0.9803

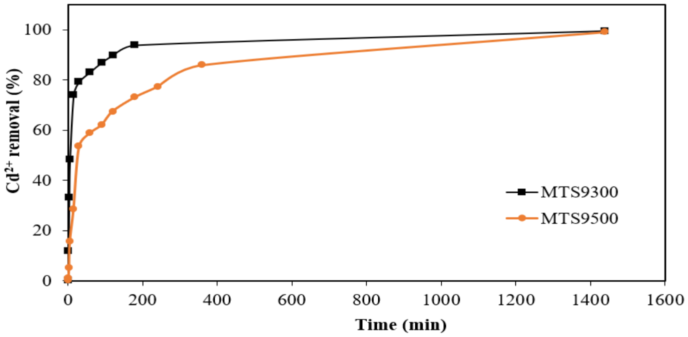

Figure 3. Removal of Cd^{2+} versus time.

3.4 Sorption isotherm

The equilibrium behaviour of Cd^{2+} ion exchange onto MTS9300 and MTS9500 resins at different temperatures (30, 40, and 50 °C) is illustrated in Figure 4 and 5. The equilibrium capacity (Q_e) of both resins initially increased with increasing equilibrium concentration (C_e) and then approached a plateau, indicating monolayer-type saturation of the available functional sites. For the MTS9300 resin, the maximum ion-exchange capacity was recorded as approximately 201 mg/g at 30 °C, 169 mg/g at 40 °C, and 126 mg/g at 50 °C. This gradual decrease with increasing temperature suggests that the ion exchange of Cd^{2+} on the iminodiacetate groups is an exothermic process, where higher temperatures slightly reduce Cd^{2+} binding affinity.

In contrast, the MTS9500 resin exhibited relatively stable and slightly increasing capacities with temperature, reaching ~191 mg/g at 30 °C, ~211 mg/g at 40 °C, and ~231 mg/g at 50 °C. This trend implies a weakly endothermic nature of Cd^{2+} exchange onto the aminophosphonic functional groups.

The equilibrium ion-exchange data obtained at 30, 40, and 50 °C were analyzed using the Langmuir and Freundlich models [27,28] to describe the interaction of Cd^{2+} ions with the functional groups of the Puromet MTS9300 and MTS9500 resins and calculated isotherm model parameters are summarized in Table 3. The resulsts indicated that the Langmuir model adequately represented the ion-exchange behavior. This suggests that the exchange occurs on a homogeneous surface with a finite number of identical active sites.

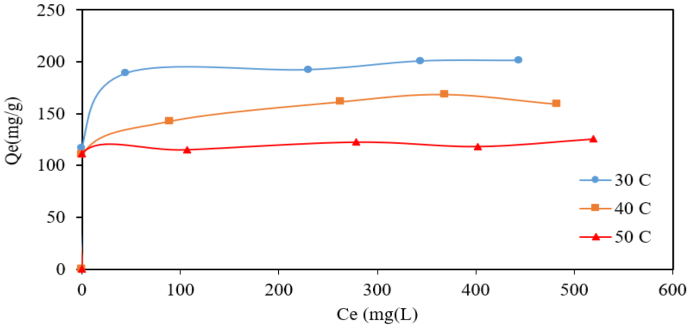

Figure 4. Sorption isotherm form MTS9300 resin.

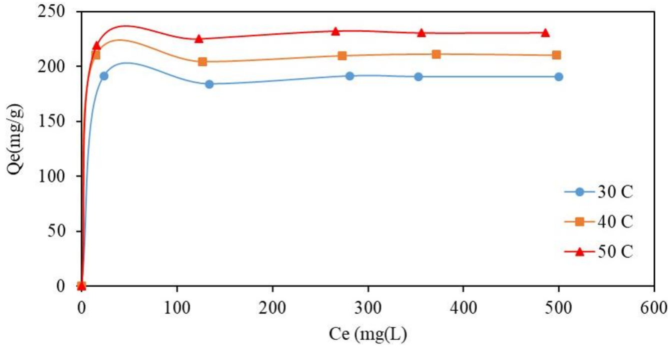

Figure 5. Sorption isotherm form MTS9500 resin.

Table 3. Adsorption isotherm parameters for sorption of Cd^{2+} ions onto ion exchange resins

Resin	Temperature		30 °C	40 °C	50 °C
MTS9300	**Freundlich Constants**	K_F (mg/g)(L/mg)$^{1/n}$	151.27	34.79	94.48
		n	20.74	3.90	23.24
		R^2	0.9903	0.9934	0.6131
	Langmuir Constants	Q_0 (mg/g)	201.33	163.74	124.19
		b (L/g)	0.3154	0.26	0.20
		R^2	0.9994	0.9974	0.9979
MTS9500	**Freundlich Constants**	K_F (mg/g)(L/mg)$^{1/n}$	161.85	183.60	209.48
		n	36.20	43.78	60.41
		R^2	0.7415	0.8442	0.9080
	Langmuir Constants	Q_0 (mg/g)	191.41	211.14	231.88
		b (L/g)	0.57	0.61	0.66
		R^2	0.9999	0.9999	0.9999

Table 4. Cd^{2+} sorption capacities of different ion exchange resins and comparison with MTS9300 and MTS9500.

Name of Resin	Functional group	Capacity for Cd^{2+} (mg/g)	Reference
MPX-310 MPX-317 TP-214	Phosphine oxide Phosphine oxide thiourea Thiourea	48.78 106.38 116.28	[29]
D-401	Iminodiacetate	224,82	[30]
C – 150 S - 930	Sulfonic acid Iminodiacetic	281.04 171.99	[31]
G-26 MTS9570	Sulphonic acid Phosphonic and Sulfonic Acid	78.125 50.02	[32]
IRA 900	Trimethylammonium	68.97	[33]
Amberjet 1200 H	Sulphonic acid	26.7	[34]
Amberlyst 15	Sulphonic acid	121	[35]
MTS9300 MTS9500	Iminodiacetic Aminophosphonic	201.33 191.44	This work

The ion-exchange capacities of different resins for Cd^{2+} removal reported in the literature are summarized in Table 4. As seen, the maximum Cd^{2+} capacities vary significantly among resins, ranging from 26.7 mg/g for Amberjet 1200 H (sulfonic acid) to 224.82 mg/g for D-401 (iminodiacetate). Such variations primarily arise from the nature of the functional groups, the degree of crosslinking within the polymer matrix, and the accessibility of the active sites to hydrated Cd^{2+} ions. Resins bearing chelating functional groups such as iminodiacetate, aminophosphonic, or thiourea generally exhibit higher exchange capacities due to their strong coordination ability toward divalent metal ions.

The newly investigated Puromet MTS9300 (iminodiacetic) and MTS9500 (aminophosphonic) resins demonstrated high Cd^{2+} capacities of 201.33 mg/g and 191.44 mg/g, respectively, which are comparable to or even higher than most commercial resins listed. This superior performance can be attributed to the efficient chelation between Cd^{2+} and the oxygen- and nitrogen-donor atoms of these weakly acidic functional groups. Furthermore, variations in resin porosity and crosslink density influence ion diffusion and site accessibility, thereby affecting overall capacity. It is also noteworthy that under certain conditions, Cd^{2+} can form negatively charged chloro-complexes (e.g., $[CdCl_4]^{2-}$) in chloride-containing media, enabling partial uptake by anion-exchange resins through electrostatic interaction. Hence, both the chemical nature of the functional group and the solution chemistry play crucial roles in determining Cd^{2+} exchange efficiency. The comparative data emphasize the importance of tailoring resin functionality and structure to optimize ion-exchange performance for cadmium removal from aqueous environments.

3.5 Thermodynamic study

Temperature significantly influences ion-exchange performance by altering the energy and mobility of solute species as well as the interaction strength between metal ions and functional groups. To elucidate the effect of temperature on Cd^{2+} removal, experiments were performed at 30, 40, and 50 °C (Figures 4 and 5). The corresponding thermodynamic parameters—Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°)—were calculated from Equations (3–6) [36] and are presented in Table 5.

$$K_e^0 = \frac{(1000\times K_g\times molecular\ weight\ of\ adsorbate)\times[Adsorbate]^0}{\gamma} \ldots (3)$$

$$\Delta G^0 = -RTLn(K_e^0) \ldots\ldots (4)$$

$$\Delta G^0 = \Delta H^0 - T \times \Delta S^0 \ldots\ldots (5)$$

$$Ln(K_e^0) = \frac{-\Delta H^0}{R\times T} + \frac{\Delta S^0}{R} \ldots\ldots (6)$$

Table 5. Thermodynamic parameters for Cd^{2+} sorption onto MTS9300 and MTS9500 resins.

Thermodynamic parameters	MTS9300	MTS9500
ΔG° (kJ/mol)	-26.37 (303 K) -26.60 (313 K) -26.83 (323 K)	-27.88 (303 K) -28.99 (313 K) -30.09 (323 K)
ΔH° (kJ/mol)	-19.32	5.61
ΔS° (J/mol.K)	23.27	110.56

For both resins, the negative ΔG° values at all studied temperatures confirm that the Cd^{2+} ion-exchange process occurs spontaneously. The magnitude of ΔG° slightly increased with rising temperature, indicating that higher thermal energy favors Cd^{2+} uptake. The MTS9300 resin exhibited a negative ΔH° value (–19.32 kJ/mol), suggesting an exothermic ion-exchange process, whereas the positive ΔH° value (5.61 kJ/mol) for MTS9500 indicates an endothermic nature, likely due to enhanced ion mobility and swelling of the resin matrix at elevated temperatures. The positive ΔS° values for both resins (23.27 J/mol. K) for MTS9300 and 110.56 J/mol. K for MTS9500) reflect an increase in randomness at the solid–solution interface during Cd^{2+} exchange.

3.6 Regeneration of exhausted resins

Efficient regeneration of ion-exchange resins is essential for their practical application and economic viability in water treatment. The regeneration performance of the MTS9300 and MTS9500 resins was evaluated using various concentrations of HCl, H_2SO_4, and NaCl solutions, and the corresponding efficiencies are summarized in Table 6. Both resins exhibited excellent regeneration performance with acidic eluents, achieving nearly 100% recovery across all HCl and H_2SO_4 concentrations tested. This high efficiency indicates that Cd^{2+} ions are effectively displaced by H^+ ions, confirming the reversible nature of the ion-exchange process and the chemical stability of the resin matrices. In contrast, NaCl solutions showed markedly lower regeneration efficiencies, increasing gradually from 12–57% for MTS9300 and 10–48% for MTS9500 as the NaCl concentration increased from 0.1 to 2.0 M. These results demonstrate that both MTS9300 and MTS9500 resins can be efficiently regenerated using dilute acid solutions.

Table 6. Regeneration performance of solutions

	Regeneration efficiency (%)	
Regeneration solution	**MTS9300**	**MTS9500**
0.1 M HCl	>99	>99
0.5 M HCl	>99	>99
1.0 M HCl	>99	>99
2.0 M HCl	>99	>99
0.1 M H_2SO_4	>99	>99
0.5 M H_2SO_4	>99	>99
1.0 M H_2SO_4	>99	>99
2.0 M H_2SO_4	>99	>99
0.1 M NaCl	12	10
0.5 M NaCl	32	27
1.0 M NaCl	44	38
2.0 M NaCl	57	48

CONCLUSIONS

Both Puromet MTS9300 and MTS9500 chelating ion-exchange resins showed excellent Cd^{2+} removal efficiency. The ion-exchange behavior depended strongly on pH due to the weakly acidic nature of their functional groups, which become protonated in acidic media and limit Cd^{2+} uptake. Kinetic data were well fitted by the pseudo-second-order model, while equilibrium data followed the Langmuir isotherm, indicating monolayer ion exchange with maximum capacities of 201.33 and 191.44 mg/g for MTS9300 and MTS9500, respectively. Thermodynamic analysis revealed spontaneous exchange for both resins, with exothermic behavior for MTS9300 and endothermic for MTS9500. Regeneration tests confirmed nearly complete recovery using dilute HCl or H_2SO_4, demonstrating the resins' high reusability and stability. Overall, both materials are promising candidates for efficient and sustainable Cd^{2+} removal from aqueous systems.

ACKNOWLEDGMENTS

This study is supported by the Scientific Research Projects Coordination Office of Ege University (Project Number: FM-YLT-2024-32476). We thank Purolite Int. Co. (Türkiye) for providing ion exchange resin samples.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI in scientific writing: During the preparation of this work, the authors used ChatGPT to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

All data generated or analysed during this study are included in this published article. More information is available from the corresponding author.

REFERENCES

[1] R. Wang, P. Sang, Y. Guo, P. Jin, Y. Cheng, H. Yu, Y. Xie, W. Yao, and H. Qian, Cadmium in food: Source, distribution and removal, Food Chem. **405**, 134666 (2023).

[2] M. M. Kwikima, S. Mateso, and Y. Chebude, Potentials of agricultural wastes as the ultimate alternative adsorbent for cadmium removal from wastewater. A review, Sci. African **13**, e00934 (2021).

[3] B. Wang, J. Lan, J. Pu, X. Liu, and B. Gong, Adsorption of cadmium ions from simulated battery wastewater by polyethylene polyamine-modified activated carbon, Water Sci. Technol. **84**, 3916 (2021).

[4] G. Genchi, M. S. Sinicropi, G. Lauria, A. Carocci, and A. Catalano, The Effects of Cadmium Toxicity, Int. J. Environ. Res. Public Health **17**, 3782 (2020).

[5] C. Wang, H. Yin, L. Bi, J. Su, M. Zhang, T. Lyu, M. Cooper, and G. Pan, Highly efficient and irreversible removal of cadmium through the formation of a solid solution, J. Hazard. Mater. **384**, 121461 (2020).

[6] F. Javaheri, Z. Kheshti, S. Ghasemi, and A. Altaee, Enhancement of Cd2+ removal from aqueous solution by multifunctional mesoporous silica: Equilibrium isotherms and kinetics study, Sep. Purif. Technol. **224**, 199 (2019).

[7] K. Attar, D. Bouazza, H. Miloudi, A. Tayeb, A. Boos, A. M. Sastre, and H. Demey, Cadmium removal by a low-cost magadiite-based material: Characterization and sorption applications, J. Environ. Chem. Eng. **6**, 5351 (2018).

[8] W. Zhang, Y. An, S. Li, Z. Liu, Z. Chen, Y. Ren, S. Wang, X. Zhang, and X. Wang, Enhanced heavy metal removal from an aqueous environment using an eco-friendly and sustainable adsorbent, Sci. Rep. **10**, 16453 (2020).

[9] A. Reda, A.-G. El-Demerdash, W. Sadik, E. El-Rafey, and T. Shoeib, Effectively eliminating lead and cadmium from industrial wastewater using a biowaste-based sorbent, Appl. Water Sci. **15**, 25 (2025).

[10] Z. Khan, A. Elahi, D. A. Bukhari, and A. Rehman, Cadmium sources, toxicity, resistance and removal by microorganisms-A potential strategy for cadmium eradication, J. Saudi Chem. Soc. **26**, 101569 (2022).

[11] M. Khairy, S. A. El-Safty, and M. A. Shenashen, Environmental remediation and monitoring of cadmium, TrAC Trends Anal. Chem. **62**, 56 (2014).

[12] N. H. A. Hamid et al., A state-of-art review on the sustainable technologies for cadmium removal from wastewater, Water Reuse **14**, 312 (2024).

[13] K. Bhattacharyya, D. Sen, A. K. Banik, and S. Ganguly, Adsorptive removal of cadmium from aqueous medium-a critical review, Phys. Chem. Earth, Parts A/B/C **134**, 103538 (2024).

[14] K. Pyrzynska, Removal of cadmium from wastewaters with low-cost adsorbents, J. Environ. Chem. Eng. **7**, 102795 (2019).

[15] M. Kumar, A. Kushwaha, L. Goswami, A. K. Singh, and M. Sikandar, A review on advances and mechanism for the phycoremediation of cadmium contaminated wastewater, Clean. Eng. Technol. **5**, 100288 (2021).

[16] A. E. D. Mahmoud, K. M. Al-Qahtani, S. O. Alflaij, S. F. Al-Qahtani, and F. A. Alsamhan, Green copper oxide nanoparticles for lead, nickel, and cadmium removal from contaminated water, Sci. Rep. **11**, 1 (2021).

[17] B. Kayranli, Cadmium removal mechanisms from aqueous solution by using recycled lignocelluloses, Alexandria Eng. J. **61**, 443 (2022).

[18] N. T. Abdel-Ghani, M. M. Hefny, G. A. El-Chaghaby, Removal of metal ions from synthetic wastewater by adsorption onto eucalyptus camaldulenis tree leaves, J. Chil. Chem. Soc. **53**, 1585 (2008).

[19] N. M. Marin, M. Nita Lazar, M. Popa, T. Galaon, and L. F. Pascu, Current Trends in Development and Use of Polymeric Ion-Exchange Resins in Wastewater Treatment, Materials (Basel). **17**, 5994 (2024).

[20] A. B. Botelho Junior, D. B. Dreisinger, and D. C. R. Espinosa, A Review of Nickel, Copper, and Cobalt Recovery by Chelating Ion Exchange Resins from Mining Processes and Mining Tailings, Mining, Metall. Explor. **36**, 199 (2019).

[21] P. Barbaro and F. Liguori, Ion Exchange Resins: Catalyst Recovery and Recycle, Chem. Rev. **109**, 515 (2009).

[22] S. Ghafoor, S. Ata, Synthesis of carboxyl-modified $Fe_3O_4@SiO_2$ nanoparticles and their utilization for the remediation of cadmium and nickel from aqueous solution, J. Chil. Chem. Soc. **62**, 3588 (2017).

[23] P. Rudnicki, Z. Hubicki, and D. Kołodyńska, Evaluation of heavy metal ions removal from acidic waste water streams, Chem. Eng. J. **252**, 362 (2014).

[24] D. Kołodyńska, P. Rudnicki, and Z. Hubicki, New approach to Cu(II), Zn(II) and Ni(II) ions removal at high NaCl concentration on the modified chelating resin, Desalin. Water Treat. **74**, 184 (2017).

[25] G. McKay, Y. S. Ho, and J. C. Y. Ng, Biosorption of Copper from Waste Waters: A Review, Sep. Purif. Rev. **28**, 87 (1999).

[26] Y. . Ho and G. McKay, Pseudo-second order model for sorption processes, Process Biochem. **34**, 451 (1999).

[27] M. Özacar and İ. A. Şengil, Adsorption of metal complex dyes from aqueous solutions by pine sawdust, Bioresour. Technol. **96**, 791 (2005).

[28] B. Alyüz and S. Veli, Kinetics and equilibrium studies for the removal of nickel and zinc from aqueous solutions by ion exchange resins, J. Hazard. Mater. **167**, 482 (2009).

[29] C. M. Simonescu, V. Lavric, A. Musina, O. M. Antonescu, D. C. Culita, V. Marinescu, C. Tardei, O. Oprea, and A. M. Pandele, Experimental and modeling of cadmium ions removal by chelating resins, J. Mol. Liq. **307**, 112973 (2020).

[30] C.-W. Wong, J. P. Barford, G. Chen, and G. McKay, Kinetics and equilibrium studies for the removal of cadmium ions by ion exchange resin, J. Environ. Chem. Eng. **2**, 698 (2014).

[31] D. Bilba, N. Bilba, and M. Albu, Kinetics of cadmium ion sorption on ion exchange and chelating resins, Solvent Extr. Ion Exch. **17**, 1557 (1999).

[32] S. Elfeghe, S. Anwar, and Y. Zhang, Adsorption and removal studies of cadmium ion onto sulphonic/phosphonic acid functionalization resins, Can. J. Chem. Eng. **100**, 3006 (2022).

[33] Y. Zhang, X. Duan, C. Hu, G. Du, and Y. Wang, Green and Cost-Effective Separation of Cadmium from Base Metals in Chloride Medium with Halide-Loaded Anion Exchanger, Processes **11**, 1051 (2023).

[34] O. E. Roshdy, Removal of uranium, cadmium and iron ions from phosphoric acid solution using amberjet 1200 H resin: an experimental, isotherm and kinetic study, J. Radioanal. Nucl. Chem. **329**, 85 (2021).

[35] A. Tunçeli, A. Ulaş, O. Acar, and A. R. Türker, Adsorption isotherms, kinetic and thermodynamic studies for cadmium and lead ions from water solutions using Amberlyst 15 resin, Turkish J. Chem. **46**, 193 (2021).

[36] E. C. Lima, A. Hosseini-Bandegharaei, J. C. Moreno-Piraján, and I. Anastopoulos, A critical review of the estimation of the thermodynamic parameters on adsorption equilibria. Wrong use of equilibrium constant in the Van't Hoof equation for calculation of thermodynamic parameters of adsorption, J. Mol. Liq. **273**, 425 (2019).