



Article The Synthesis and Effect of Silver Nanoparticles on the Adsorption of Cu²⁺ from Aqueous Solutions

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Abstract: The adsorption of Cu^{2+} ions from an aqueous solution using AgNPs synthesized from *Convolvulus arvensis* leaf extract was investigated. The characterization of AgNPs was investigated before and after the adsorption of Cu^{2+} ions via Fourier-transform infrared spectroscopy (FTIR), energy-dispersive X-ray spectroscopy (EDS), and scanning electron microscopy (SEM) analyses. The adsorbent contained various functional groups in addition to the AgNPs, which contributed to the Cu^{2+} ions adsorption. The silver nanoparticle surface consisted of spherical particles and deep pores, which adsorbed numerous Cu^{2+} ions. The influences of dosage, pH, and contact time on adsorption of 10 and 50 mg/L Cu^{2+} at 298 K, and initial Cu^{2+} concentrations at 298 and 323 K were studied. It was found that the highest percentage of Cu^{2+} ions and 0.2 g of AgNPs, at pH 12 and 298 K. A pseudo-second kinetics model offered the most accurate description of the process of adsorption. The process of Cu^{2+} adsorption more resembled a Langmuir rather than a Freundlich isotherm model, including chemical and physical mixed adsorption (mixed adsorption) processes, and was exothermic and spontaneous.

Keywords: AgNPs; Cu²⁺; green synthesis; adsorption; nanoparticles

1. Introduction

The water contamination resources with heavy metals is a serious problem of environments worldwide. Numerous heavy metals are known to be toxic, dangerous, and non-degradable. Copper is used to manufacture various products, such as metal wires, sheet metals, metal pipes, metal coatings, and fertilizers. It is released into water, where it forms copper compounds or becomes bound to the molecules suspended in the water [1]. Although copper is necessary for human health, it may cause anemia, gastrointestinal damage, and dermatitis if its concentration exceeds the permissible limit. It can also destroy fish and marine plants if it is found in a large amount in sea water [2]. Therefore, copper adsorption from aqueous solutions is of great importance, and to find methods to do this, several technologies have been developed, including adsorption, ion exchange, electrochemical processing, and nanotechnology [3]. Nanotechnology has developed rapidly in various application areas, such as industry, medicine, and water treatment [4].

Researchers are interested in studying water treatment with the use of chemical, physical, and nanotechnological methods. One example of nanomaterials that have been exploited for this purpose is silver nanoparticles (AgNPs) [5]. AgNPs are characterized by their anti-bacterial properties and easy separation. Moreover, they possess catalytic activity and a relatively high adsorption capacity and surface area for their small size [6]. In addition to their use in water and air purification, they are used in biomedical applications, food production, cosmetics, household products, and the clothing industry [7].

Biosynthesis is preferable compared to other methods [8] because it is environmentally friendly, cost effective, and less time-consuming. Biological materials include plant extracts, bacteria, fungi, enzymes, and other substances [9] such as *Ganoderma applanatum* [10], *Staphylococcus aureus, Kocuria rhizophila* and *Bacillus thuringiensis* [11], *Phoma* [12], and *Endophytic fungi* [13]. Plant extracts are considered to be the best biological materials because they are abundant and their chemical compositions facilitates the formation of nanoparticles by functioning as reducing agents that reduce silver ions to the silver element. Plant extracts are also inexpensive and quick to prepare compared to microbes that require sterilization conditions and time to produce them [8], and possess active components that improve the effectiveness of nanoparticles [14,15], such as extracts of *Artemisia annua* and *Sida acuta* [16], *Phoenix dactylifera* fruits [3], *Eriobotrya japonica* (Thunb.) [17], *Acalypha hispida* [18], and *Cassia auriculata* [19].

Convolvulus arvensis (field bindweed) is a climbing plant that covers wide areas of building frontages, owing to its aesthetic value. Some types of *C. arvensis* have medicinal uses, whereas others are highly toxic [20].

This study aimed to synthesize AgNPs from an extract of *C. arvensis* leaves and to test its effectiveness as an adsorbent material for the treatment of aqueous solutions from dissolved Cu2+ ions. The *C. arvensis* leaf extract, AgNPs, and Cu²⁺ were characterized via Fourier-transform infrared spectroscopy (FTIR), energy-dispersive X-ray spectroscopy (EDS) and SEM analysis. The adsorption of Cu²⁺ by the AgNPs was studied through of the effects of the dosage, pH, adsorption isotherm thermodynamic, and kinetic models.

2. Experimental

2.1. Materials

The chemicals Cu(Cl)₂·4H₂O (98%) and AgNO₃ were purchased from Techno Pharmchem (Delhi, India), HCl (37%), and NaOH (97%) were purchased from Panreac Quimica (Barcelona, Spain).

2.2. Preparation of the C. arvensis Leaf Extract

The leaves of a *C. arvensis* were collected, washed, dried, and cut into small pieces. *C. arvensis* extract was prepared using distilled water, and the mixture was stirred for 30 min at 60 °C. It was filtered using Whatman No. 1 filter paper (Figure 1) [20].



Figure 1. Convolvulus arvensis leaf extract.

2.3. Synthesis of the AgNPs

For the preparation of AgNPs, a 5 mL of the AgNO3 (1 M) and 10 mL of 1 M NaOH were added to 10 mL of the *C. arvensis* leaf extract, with continuous stirring for 15 min and heated to 50 °C to ensure the formation of AgNPs was complete and that they were stable. The solution rapidly changed color, indicating the direct formation of silver. The centrifugation was used to separating AgNPs from the solution, then the precipitate was dried and kept for later use (Figure 2).



Figure 2. The synthesis of AgNPs.

2.4. Preparation of the Test Solution

The stock solution of Cu^{2+} (1000 mg/L) was prepared. The stock solution was diluted with distilled water for the initial solutions with two different concentrations (10 and 50 mg/L).

Experiments on the adsorption of Cu^{2+} from aqueous solutions were conducted at both 10 and 50 mg/L concentrations at 298 K and an initial pH of 7. The effects of the AgNPs dosage (0.05, 0.1, 0.15 and 0.2 g) and the pH (2, 5, 7, 9, 12) using 0.2 g of AgNPs at 298 K, respectively, on the Cu^{2+} adsorption were investigated. The pH adjustments were adjusted using 1 M of NaOH and 1 M of HCl. The contact time effect on the Cu^{2+} adsorption was studied for 150 min. The effect of the Cu^{2+} initial concentration (from 10 to 50 mg/L) on the Cu^{2+} adsorption using the AgNPs (0.2 g) was studied at an initial pH of 7, and at temperatures of 298 K and 323 K. The mixtures were shaken at 100 rpm for 3 h using an orbital "rotaterm" and a linear shaker, and were then filtered. The concentrations of Cu^{2+} were determined via plasma mass spectrometry (inductively coupled plasma, ICP).

The amount of the Cu²⁺ absorbed (q_e (mg/g)) was calculated using the following equation:

$$q_e = \frac{(C_0 - C_e) V}{m},\tag{1}$$

where C_0 and C_e (mg/L) are the concentrations of initial and equilibrium, respectively, V (L) is the solution volume, and m is the adsorbent mass (g).

The adsorption percentage of Cu^{2+} (% $Ads_{(Cu}^{2+})$) was calculated as follows:

% Ads_(Cu²⁺) =
$$\frac{(C_0 - C_e)}{C_0} \times 100.$$
 (2)

To describe the adsorbent behavior, the models of four kinetic and two adsorption isotherm were used and, to describe the adsorption type, the thermodynamic parameters (ΔG° , ΔH° and ΔS°) were calculated.

2.5. AgNPs Characterization

The FTIR spectra and the surface morphology were investigated for AgNPs. FTIR was performed using a FTIR spectrophotometer (type spectrum 100 FT-IR spectrometer, PerkinElmer, Waltham, MA, USA) over a wavenumber range of 400–4000 cm⁻¹. Energy dispersive spectroscopy (EDS) and SEM were performed using a JSM-6380 LA model scanning electron microscope (JEOL, San Diego, CA, USA) at an accelerating voltage of 0.5–30 kV and a high resolution of 3.0 nm.

3. Results and Discussion

3.1. Characterization of the Adsorbent

Figure 3 presents the functional groups in the AgNPs before and after the adsorption of Cu^{2+} . It was noted that the peaks at 3423, 2925, 1623, 1384, 1321, 1073, 766, 606, and 514 cm⁻¹ were referred to the functional groups in the AgNPs synthesized using the *C. arvensis* leaf extract. The stretching of the functional groups in the AgNPs were associated with the peaks at 3408, 2918, 1624, 1324, 1000, 782,

and 538 cm⁻¹ arising after the Cu²⁺ adsorption. It was observed that the peaks at 3423 and 3408 cm⁻¹ in the AgNPs spectra before and after the Cu²⁺ adsorption, respectively, appeared as a result of the stretching of the N–H or O–H groups. The secondary peaks at 2925 and 2918 cm⁻¹ were caused by the stretching of the C–H groups. The band regions at 1623 and 1624 cm⁻¹ were related to the presence of C=O bonds. In addition, after the adsorption of Cu²⁺ ions, the two absorption peaks that appeared at 1384 and 1321 cm⁻¹ in the AgNPs spectrum agreed to the groups of N=O and N–O, respectively, whereas the peak at 1324 cm⁻¹ was ascribed to the N–O band of the AgNPs [3,4,8,21]. The peaks at 1073 and 1000 cm⁻¹ were due to the N–H, C–N, or C–O groups extending, and the peaks at 766, 782, and 514–538 cm⁻¹ were due to the stretching of the H₃CO and C–H groups [14,22].



Figure 3. A Fourier-transform infrared spectroscopy (FTIR) analysis of the functional groups in AgNPs before and after Cu^{2+} was adsorbed.

The above results demonstrate that the presence of the functional groups, including carboxyl, facilitate the adsorption process of Cu^{2+} via ion exchange. Moreover, the presence of the hydroxyl groups in the adsorbent allows the coordination bonds to form with the Cu^{2+} ions.

EDS was used to analyze the AgNPs synthesized using the *C. arvensis* leaf extract before the Cu^{2+} ions adsorption and after, as displayed in Figure 4a. The figure presents a high-intensity peak in the optical absorption range at 3 keV for the adsorption range of AgNPs, indicating that the C. arvensis leaf extract successfully contributed to the synthesis of AgNPs. The spectrum also identifies C, O, Na, Ca, Cl, and Cd peaks, indicating that the AgNPs contain organic and inorganic compounds [8,21,23]. The EDS spectrum of the AgNPs after the adsorption of Cu^{2+} (Figure 4b) presented a decrease in the percentages of the Ag, Na, and Cd elements, and the emergence of a Cu^{2+} peak indicated the adsorption of Cu^{2+} ions on the AgNPs' surface [23].

The surface morphology of the AgNPs was performed using a SEM analysis before and after the Cu2+ adsorption. Spherical AgNPs were observed to form with the *C. arvensis* leaf extract (Figure 5a), which confirmed that the synthetic AgNPs were well crystallized [6,24]. Figure 5b also presents the change in the surface morphology of the AgNPs after the adsorption of Cu^{2+} ions [22]. Changes in the shapes of the crystals and the pores on the surface were observed, as well as the surface coverage after the adsorption of most Cu^{2+} ions [22,25].



Figure 4. Energy-dispersive X-ray spectroscopy (EDS) images of AgNPs (0.2 g) before (**a**) and after Cu^{2+} (10 mg/L) was adsorbed (**b**) for 3 h at 298 K.



Figure 5. SEM images of AgNPs (0.2 g) before (**a**) and after Cu²⁺ (10 mg/L) was adsorbed (**b**) for 3 h at 298 K.

3.2. Effect of the AgNPs Dosage

The AgNPs' dosage effect on the adsorption of Cu^{2+} was studied. As presented in Figure 6a, when the AgNPs' dosage increased, the Cu^{2+} adsorption increased. Specifically, the percentage of Cu^{2+} adsorption increased from 31% to 91% with a 10 mg/L concentration and from 23% to 73% with a 50 mg/L concentration. The increase in the percentage of Cu^{2+} adsorption was due to the increase in the area of the AgNPs' surface and the consequent increase in the number of active sites and their availability for ion and electronic exchanges with the Cu^{2+} ions that were dissolved in the aqueous solutions [25,26].

3.3. Effect of the pH

An aqueous solution's pH is important in adsorption processes, because pH affects the type of charge of the adsorbent surface, and thus the adsorption ratio of Cu^{2+} from it. The experiments on the pH effect were conducted at various values of pH between 2 and 12, to evaluate the Cu^{2+} adsorption from aqueous solutions by the AgNPs. The percentage of the Cu^{2+} adsorption increased rapidly with the increase in the pH from 2 to 7; subsequently, with the pH increased from 7 to 12, the Cu^{2+} adsorption increased slightly, as displayed in Figure 6b. The reason for the increase in the percentage of Cu^{2+} adsorption is due to the increase in the concentration of the OH^- ions on the AgNPs' surface, with an increased pH from 2 to 12, thus charging the surface with a negative charge, which increased the potential of the Cu^{2+} adsorption on the AgNPs' surface. [27]. Moreover, the presence of functional groups in the *C. arvensis* leaf extract, such as C=O and C–O, enhanced the ionic bonding with Cu^{2+} ions. Thus, adsorbed amount of the Cu^{2+} on the AgNPs' surface increased [15].

3.4. Effect of the Contact Time

The contact time effect, which ranged from 30 to 180 min, on the Cu^{2+} adsorption by the AgNPs was investigated. Figure 6c shows that the adsorption percentage of Cu^{2+} increases for both the low and high concentrations (10 and 50 mg/L). The percentage of Cu^{2+} adsorption increased rapidly during the initial stage (up to 60 min). This is because the active sites on the AgNPs' surface were available. Subsequently, the adsorption of Cu^{2+} for both the concentrations decreased as the availability of the active sites for adsorption reduced over time [25].



Figure 6. Effect of AgNPs' dose on the adsorption percentage of Cu^{2+} . (a) The effect of pH, (b) the contact time, (c) the Cu^{2+} concentration and temperature, and (d) the adsorption percentage of Cu^{2+} by AgNPs (0.2 g).

3.5. Effects of the Cu^{2+} Concentration at 298 and 323 K

The effect of the initial concentration of Cu^{2+} ions at 298 and 323 K was studied. Figure 6d shows that the percentage of the Cu^{2+} adsorption decreased from 91.10% to 80.06% as the concentration increased from 10 to 50 mg/L. This was due to an increased competitive dispersion of the Cu^{2+} ions in the pores available on the AgNPs' surface, thus preventing them from reaching the deep pores of the AgNPs [27]. The adsorption of Cu^{2+} by the AgNPs also decreased with an increasing temperature, from 298 to 323 K (Figure 6d), possibly owing to a decrease in the surface activity, dissolution of the active sites on the adsorbent surface, or bond breakage with the increased temperature [15].

3.6. Kinetic Models

According to the data obtained from investigating the effect of time on the Cu²⁺ adsorption by AgNPs, different kinetic models were used to understand the Cu²⁺ adsorption mechanism by AgNPs to identify the rate-limiting step. The pseudo-first-order (PFO), pseudo-second-order (PSO), intraparticle diffusion (IPD), and liquid film diffusion (LFD) kinetic models are expressed as follows [28,29]:

$$\log(q_e - q_t) = \log q_e - \frac{K_1 t}{2.303},$$
(3)

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e},$$
(4)

$$ln\left(1-F\right) = -K_{lfd} t + C_{lfd},\tag{5}$$

$$q_t = K_{ipd} t^{1/2} - C_{ipd}, (6)$$

where q_e and q_t represent the adsorption amounts of Cu²⁺ at equilibrium and at time *t*, respectively, K_1 is the rate constant of the pseudo-first-order reaction, K_2 is rate constant of the pseudo-second-order reaction, K_{ipd} is the intraparticle diffusion coefficient, C_{ipd} is a constant that provides information on the thickness of the boundary layer, *F* is the fractional attainment of equilibrium ($F = q_t/q_e$), K_{lfd} is the rate constant of the liquid film diffusion reaction, and C_{lfd} is the constant of the boundary layer.

Figure 7 shows the four kinetic diagrams of the Cu^{2+} (10 and 50 mg/L) adsorbed by AgNPs. The parameters for the four kinematic models are recorded in Table 1. The experimental data did not agree with the pseudo-first-order model. However, the kinetic data fitted well with the pseudo-second-order model: R^2 values were 0.999 with 10 mg/L and 0.984 with 50 mg/L of Cu^{2+} [30]. The calculated q_e values were 0.24 mg/g with 10 mg/L and 2 mg/g with 50 mg/L of Cu^{2+} , which were consistent with the experimental q_e values of 0.24 mg/g for 10 mg/L and 2 mg/g for 50 mg/L of Cu^{2+} [7]. Figure 7 evident that the AgNPs is adsorbed Cu^{2+} ions in two or more steps. This suggests that the Cu^{2+} adsorption process involves multiple mechanisms. The first step is the diffusion of Cu^{2+} on the AgNPs surface, and the next step is the spread of Cu^{2+} by the AgNPs based on the liquid film diffusion model (R^2) were 0.960 and 0.986 for 10 and 50 mg/L of Cu^{2+} , respectively, indicating that the film diffusion is one of the factors that controls the process of the adsorption of Cu^{2+} [31].



Figure 7. Four kinetic model plots (pseudo-first-order (PFO), pseudo-second-order (PSO), intraparticle diffusion (IPD), and liquid film diffusion (LFD)) for the adsorption of Cu^{2+} by AgNPs (adsorbent dosage, 0.2 g; concentration of Cu^{2+} , 10 and 50 mg/L at pH 7, and 298 K).

	Adsorbent		
Kinetic Models	10 mg/L	50 mg/L	
q _{e,exp} mg/g	2.278	9.225	
Pseudo-First-Order			
<i>q</i> e, cal mg/g	1.401	6.391	
K_1, \min^{-1}	0.031	0.031	
R^2	0.996	0.945	
Pseudo-Second-Order			
<i>q</i> _{e,cal} mg∕g	2.470	10.823	
K_2 , g/mg min	0.033	0.004	
R^2	0.999	0.984	
Intraparticle Diffusion			
Step 1			
K_{ind} , mg/g.min ^{1/2}	0.149	1.419	
C, mg/g	0.898	2.437	
R^2	1	1	
Step 2			
K_{ipd} , mg/g.min ^{1/2}	0.024	0.074	
<i>C,</i> mg/g	1.979	8.259	
R^2	0.932	0.975	
Liquid Film Diffusion			
K_{lfd} , min ⁻¹	0.031	0.031	
C, mg/g	0.487	0.368	
R^{2}	0.996	0.945	

Table 1. Parameters of four kinetic models.

3.7. Adsorption Isotherm Models

The adsorption isotherm models of Langmuir and Freundlich were used to illustrate the mechanism of Cu^{2+} adsorption using the AgNPs.

The Langmuir and Freundlich adsorption isotherm models are expressed as follows [32]:

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m},\tag{7}$$

$$R_L = \frac{1}{1 + K_L C_0},$$
(8)

$$\log q_e = \log K_F + \frac{1}{n} \log C_e, \tag{9}$$

where C_e (mg/L) is the concentration of the adsorbate at equilibrium, q_e is the capacity of adsorption at equilibrium, q_m is the maximum capacity of adsorption, K_L is the constant of Langmuir adsorption at equilibrium, and n is the coefficient of Freundlich at equilibrium.

The Langmuir isotherm hypothesis is valid for a monolayer forming on the adsorbent surface, whereas the Freundlich isotherm is an experimental equation that is applicable to a multilayer adsorption process.

Figure 8, shows that there is a linear relationship between the C_e/q_e and C_e and between the log q_e and log C_e for the Cu²⁺ adsorption by the AgNPs. The plots slopes and the correlation coefficients (R^2) are recorded in Table 2. The R^2 values indicated that the Langmuir imore suitable for the experimental than the Freundlich; moreover, the theoretical maximum adsorption capacity of a monolayer coverage (q_m) was shown to be higher than the experimental capacity [33].





Figure 8. The adsorption isotherm model plots (Langmuir and Freundlich) for the adsorption of Cu^{2+} on AgNPs (adsorbent dosage, 0.2 g; concentration of Cu^{2+} , 10 and 50 mg/L; pH 7; contact time 3 h, at 298 K).

Table 2. Adsorption isotherm parameter
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Tomporaturo	Langmuir Model			Freundlich Model			
Temperature	q _{max} (mg/g)	<i>K_L</i> (L/mg)	R_L	R^2	$K_F ({ m mg/g}) ({ m L/mg})^{1/n}$	n	R^2
298 K	12.092	0.243	0.254	0.998	2.585	1.883	0.980
323 K	9.980	0.135	0.426	0.996	1.517	1.807	0.959

The physicochemical constant of dimensional was applied as a factor of separation (R_L) to determine whether the adsorption process was favorable, which is expressed in Equation (8) [31]. R_L , the separation factor for the adsorption of Cu²⁺ by the AgNPs, was 0.254 at 298 K and 0.426 at 323 K, indicating a favorable adsorption.

Generally, R_L indicates that the isothermal type is favorable (0 < R_L < 1), linear (R_L = 1), unfavorable (R_L > 1), or irreversible (R_L = 0).

The values of n to assess the adsorption process suitability were 1.883 at 298 K and 1.807 at 323 K, indicating that the Cu^{2+} ions adsorption by the AgNPs is favorable [30].

Generally, the value of n is the adsorption intensity: n = 1 indicates the homogeneity of adsorption sites and lack of interaction between occupied sites; when n is between 1 and 10 it indicates a favorable adsorption, and when n < 1 a cooperative adsorption is indicated. From the above results, it was found that the Cu²⁺ ions adsorption by the AgNPs is a favorable process and that the Cu²⁺ ions are adsorbed on the AgNPs surface as monolayers and multilayers [15].

3.8. Thermodynamic Models

Thermodynamic investigations are also important approaches to describe the spontaneous processes of the Cu²⁺ adsorption from aqueous solutions by the AgNPs. Based on the results obtained from studying the effect of the initial Cu²⁺ concentration on the Cu²⁺ adsorption by the AgNPs at 298 and 323 K, the Gibbs free energy (ΔG°), the enthalpy (ΔH°), and the entropy (ΔS°), were calculated using the following equations [33,34]:

$$\Delta G^{\circ} = -RTln(K_L M_{adsorbate} \times 10^3 \times 55.5), \tag{10}$$

$$ln\left(\frac{K_1}{K_2}\right) = \Delta H^{\circ}_{ads}\left(\frac{1}{T_2} - \frac{1}{T_1}\right),\tag{11}$$

$$\Delta G^{\circ}_{ads} = \Delta H^{\circ}_{ads} - T \Delta S^{\circ}_{ads}, \qquad (12)$$

where *M* is the molecular weight of the adsorbate, *K* (L/mg) is the equilibrium constant of the experimental, 55.5 (mol/L) is the concentration of water, *R* is the constant of the universal gas (8.314 mol/K), and *T* (K) is the solution temperature absolute.

The values of ΔG° , ΔH° , and ΔS° are listed in Table 3. The negative values of ΔG° indicate that the process of Cu²⁺ ions adsorption by the AgNPs is natural and spontaneous [35], and because these values ranged from -40 to -20 kJ mol⁻¹, it suggests that the adsorption is a mixed type (physicochemical adsorption). Generally, the values of ΔG° of less than -20 kJ mol⁻¹, more than -40 kJ mol⁻¹, and between -40 and -20 kJ mol⁻¹ indicate that the adsorption is physical adsorption, chemical adsorption, and physicochemical adsorption, respectively.

ΔG° (kJ/mol)		$\mathbf{A} \mathbf{H}^{\circ} \left(\mathbf{V} \mathbf{I} / \mathbf{m} \mathbf{o} \right)$	ΔS° (I/m al V)	
298 K	323 K		$\Delta S (j/mor K)$	
-33.850	-32.395	-18.803	50.493	

Table 3. Thermodynamic parameters.

In addition, the negative values of ΔH° indicate that the adsorption is exothermic, and the positive values of ΔS° indicate an increase in the randomness because of the competition of the Cu²⁺ ions on the active AgNPs' surface sites [35].

4. Conclusions

The results of FTIR, EDS, and SEM indicated that spherical AgNPs synthesized with *C. arvensis* leaf extract containing organic and inorganic compounds and used for the adsorption of Cu²⁺ ions from aqueous solutions. The results demonstrated that the highest efficacy of the AgNPs for adsorbing Cu²⁺ ions was 98.99% at pH 12 and 298 K. The experimental data agree well with the pseudo-second-order model. The AgNPs adsorbed the Cu²⁺ ions by diffusion on the AgNPs surface and within the pores, and the film diffusion was one of the processes that controlled the Cu²⁺ adsorption. The Langmuir model was agreed more with experimental results than the Freundlich model in its explanation of Cu²⁺ adsorption by AgNPs. The values of q_m were determined as 12.09 mg/g at 298 K and 9.98 mg/g at 323 K. The negative ΔG° and ΔH° values and the positive of ΔS° value, confirmed that the process of the Cu²⁺ ions adsorption on the surface of the AgNPs was a physicochemical adsorption, and both exothermic and spontaneous. The results obtained conclude that AgNPs can be applied for Cu²⁺ adsorption from aqueous solutions.

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