

Adsorptivity and selectivity of heavy metals Cd(II), Cu(II), and Zn(II) toward phosphogypsum

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ABSTRACT

The phosphogypsum (PG) is a waste by-product of the wet process of phosphoric acid production. In this study, phosphogypsum was prepared and used as an adsorbent for the removal of cadmium, copper, and zinc ions from aqueous solutions. First, the phosphogypsum was characterized, before and after the adsorption process, by Fourier transform infrared spectroscopy and scanning electron microscopy. Then the effect of the initial pH of the metal ions solutions on the adsorption process has been studied. Second, the competitive adsorption of metal ions on phosphogypsum in the ternary mixture was investigated and compared with non-competitive adsorption. The results show that the adsorption of metal ions by phosphogypsum depends on the solution pH. The selectivity order of the adsorbent is $Cd^{2+} > Cu^{2+} > Zn^{2+}$. From these results, it can be concluded that the phosphogypsum could be a low-cost material for heavy metals removal, especially cadmium ion, from aqueous basic solutions.

Keywords: Adsorption; Phosphogypsum; Selectivity; Heavy metals

1. Introduction

The use of low-cost adsorbents has been investigated as a replacement for costly current methods. Natural materials or waste products from certain industries with a high capacity for heavy metals can be obtained, employed, and disposed of with little cost. Heavy metals are often discharged by a number of industries, such as metal plating facilities, mining operations, and tanneries, this can lead into the contamination of freshwater and marine environment [1]. Heavy metals are not biodegradable and can lead to accumulation in living organisms, causing various diseases and disorders [2]. Heavy metals like zinc and cadmium, even at low concentrations are serious threats to

living organisms through their being stimulating, property aggregation ability, carcinogenicity, and mutagenesis [3].

Generally, many methods such as coagulation, membrane process, oxidation and reduction, ion exchange, adsorption, and photocatalytic degradation are used for heavy metals removal from water and wastewater [4–9]. However, most of them do not lead to a satisfactory depollution considering the operational costs [10]. This has encouraged researchers to find efficient and inexpensive materials.

Adsorption is a process during which an adsorbate accumulates on the surface of another substance [11]. In fact, adsorption is the function of transferring from liquid to solid phase. It is an important phenomenon in many physical, chemical, and biological processes in nature. Adsorption is

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also widely used in water and wastewater treatment [12]. In recent times, many researches on adsorption of heavy metals have focused on adsorption efficiency onto different adsorbents and to find the adsorbents that are effective, affordable, and capable for recovery or recycling [13–17]. Interest has arisen in the investigation of some unconventional methods and low cost materials for scavenging heavy metal ions (HMI) from industrial waste waters [18]. In general, an adsorbent can be assumed as a low cost if it requires little processing, is abundant in nature, or is a by-product or waste material from industry [2].

The phosphogypsum is a by-product of the reaction between sulfuric acid and phosphate rocks to produce phosphoric acid, and has serious storage problem. Its use for the removal of heavy metals has been intensively studied. Until now, many researches have focused on the adsorption of single metal ion on phosphogypsum from aqueous solutions, but the adsorption study for competitive multi-metal ion removal have not yet been conducted. The study on the removal of nickel, cadmium, copper, lead, and zinc by phosphogypsum had good results [19–21].

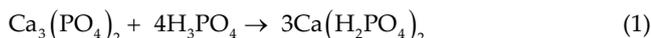
The main purpose of this research was firstly to investigate the efficiency of phosphogypsum for the removal of Cd^{2+} , Cu^{2+} , and Zn^{2+} from aqueous solutions and secondly to evaluate the selectivity and competitiveness potential of Cd^{2+} , Cu^{2+} , and Zn^{2+} to be immobilized. The effective parameters during the adsorption process such as contact time and solution pH were also studied.

2. Experimental

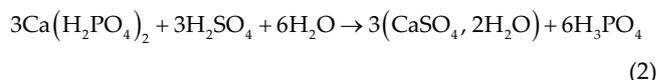
2.1. Preparation of phosphogypsum

The phosphogypsum used in this study has been prepared by a two step synthesis (wet process) according to the following overall reaction:

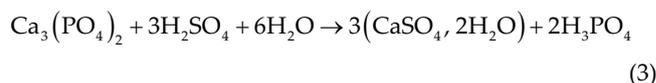
First step:



Second step:



Overall reaction:



In a three-neck round-bottom flask, an amount of phosphate is attacked with sulfuric acid in the presence of industrial phosphoric acid (P_2O_5 , 30%). The prepared solution was mechanically stirred at 80°C . After 1 h of maturation, the solution was filtered while hot to recover the first filtrate which is phosphoric acid. The phosphogypsum was washed with bidistilled hot water and pure acetone, and then dried at 80°C in oven for 12 h. The method of preparation of phosphogypsum is shown in Fig. 1.

2.2. Chemical reagents and adsorption experiments

2.2.1. Chemical reagents

All chemicals were of analytical grade. Stock solutions of HMI ($1,000 \text{ mg L}^{-1}$) were prepared from ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$), ($\text{CdCl}_2 \cdot \text{H}_2\text{O}$), and ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$). The working standard and experimental solutions were prepared daily by dilution of the stock solutions with DI-water prior to use.

2.2.2. Adsorption experiments

For adsorption kinetic, the mixture of the test solution 100 mL (200 mg L^{-1}) and phosphogypsum (2 g) was stirred in a shaker at 150 rpm and at $25^\circ\text{C} \pm 2^\circ\text{C}$ continuously for 3 h. Separate samples were drawn after 5, 10, 20, 40, 60, 120, and 180 min intervals. The suspension was filtered. The amount

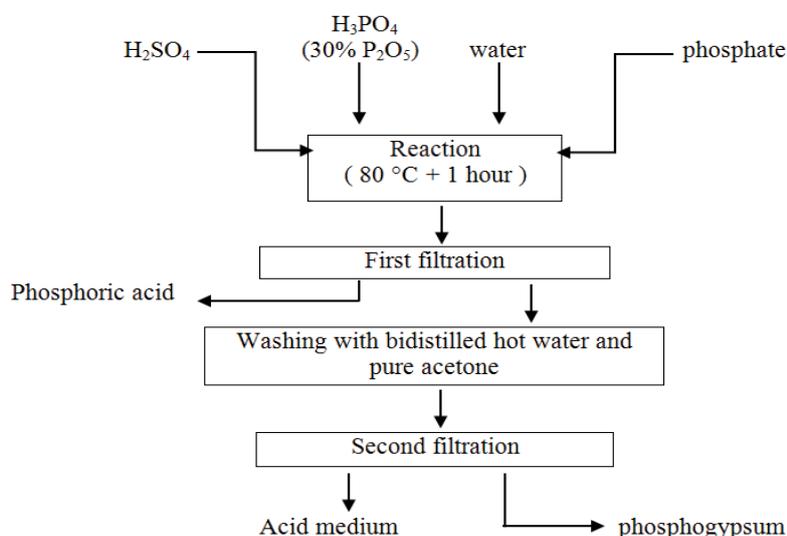


Fig. 1. Diagram of preparing phosphogypsum.

of metals was then analyzed using atomic absorption spectroscopy inductively coupled plasma atomic emission spectroscopy.

In order to investigate the effect of pH on cadmium, copper, and zinc adsorption onto phosphogypsum, metal solutions of 100 mL in volume and 200 mg L⁻¹ in concentration were used at pH ranging from 2 to 12 at 25°C ± 2°C. In the experiments, phosphogypsum content was kept constant (2 g) and agitation time was determined to be 1 h. pH adjustments were carried on using 0.1 N hydrochloric acid (HCl) and 0.1 N sodium hydroxide (NaOH).

Langmuir and Freundlich adsorption isotherm models were used at constant temperature (25°C). The ratio of adsorbent to solution volume was 20 g L⁻¹ for previously determined contact time using solutions of concentration varying from 100 to 500 mg L⁻¹.

2.2.3. Calculating heavy metals removal

The adsorbent capacity of phosphogypsum has been determined in both simple (Cd²⁺ or Cu²⁺ or Zn²⁺) and ternary (Cd²⁺, Cu²⁺, and Zn²⁺) mixing solutions. In order to obtain the adsorption capacity, the amount of ions adsorbed per mass phosphogypsum (mg g⁻¹) was evaluated using the following expression:

$$q_e = \frac{C_0 - C_e}{m} \times V \quad (4)$$

where q_e is the amount of heavy metal adsorbed at equilibrium (mg g⁻¹), C_0 is the initial concentration (mg L⁻¹), C_e is the equilibrium concentration (mg L⁻¹), V is the volume of the reaction mixture, and m is the mass of adsorbent used (g).

3. Results and discussion

3.1. Adsorbent: phosphogypsum (PG)

The phosphogypsum before and after the adsorption process was characterized using Fourier transform infrared

spectroscopy (FT-IR). The morphological characteristics were evaluated by employing scanning electron microscopy (SEM).

3.1.1. FT-IR analysis of phosphogypsum

Infrared spectra of the adsorbent before and after the adsorption are recorded in the area ranging from 4,000 to 400 cm⁻¹. The spectra obtained for the PG is shown in Fig. 2.

The FT-IR spectrum of phosphogypsum has an intense peak around 1,155.39 cm⁻¹, the PG has an additional two weak bands at 673.65 and at 2,388.09 cm⁻¹ corresponding of SO₄²⁻, the PG has also two bands characteristic of H₂O at 3,433.63 and 1,637.35 cm⁻¹ [22,23].

After the adsorption, the spectra have the same shape as that of calcium sulfate, with a slight shift and variation in intensity of some vibration bands. This discrepancy is probably due to the existence of exchange reactions between Ca²⁺ and Cd²⁺, Cu²⁺, and Zn²⁺.

The observed band at 884.19 cm⁻¹ is probably due to the vibrations of HPO₄²⁻ which absorb in the same region. The intensity of this band varies after adsorption of cadmium, copper, and zinc into the calcium sulfate crystal, these bands variations probably come from a change of environment of the metals ions in the brushite.

The observed band at 3,433.63 cm⁻¹ is usually attributed to symmetric stretching vibrations of OH⁻ ions. This suggests that the adsorption of metals ions significantly alters the intensity of this band and of that corresponding to the OH groups, and the Cd²⁺, Cu²⁺, and Zn²⁺ are exchanged as (CdSO₄), (CuSO₄), and (ZnSO₄), respectively.

3.1.2. Morphological characteristics

The morphological characteristics of the adsorbent were evaluated by using an SEM. SEM images for phosphogypsum before and after adsorption of Cu²⁺, Cd²⁺, and Zn²⁺ are shown in Figs. 3a–d. As shown in Fig. 3a phosphogypsum

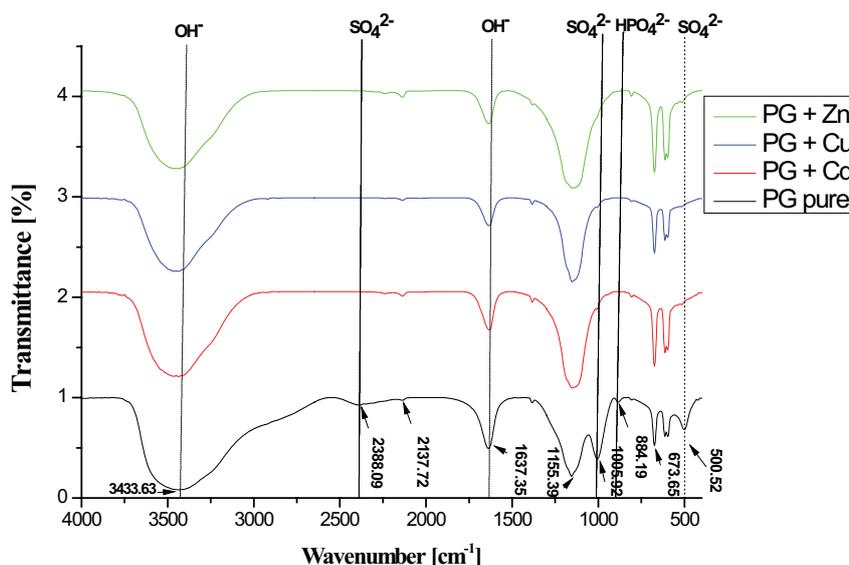


Fig. 2. FT-IR spectra of PG before and after adsorption of Cd²⁺, Cu²⁺, and Zn²⁺.

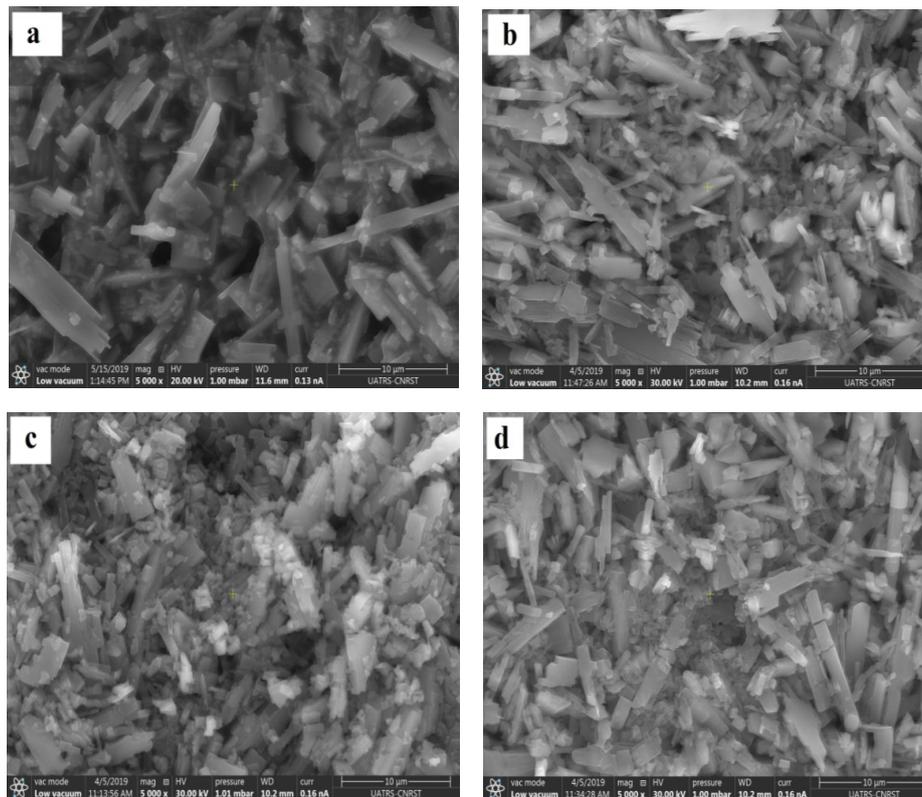


Fig. 3. SEM images of PG (a) before adsorption, (b) after adsorption of Cd^{2+} , (c) after adsorption of Cu^{2+} , and (d) after adsorption of Zn^{2+} .

has a well-defined crystalline structure with the majority of rhombic and hexagonal shape crystals [24] and containing open pores [23], which may promote the metal adsorption. The comparison of phosphogypsum images before and after adsorption of Cu^{2+} , Cd^{2+} , and Zn^{2+} (Figs. 3b–d) shows all ions appeared to cover the surface of phosphogypsum and penetrate into the crystals.

3.2. Effect of contact time

Contact time is an important parameter because this factor determines the adsorption kinetics of adsorbate at a given initial concentration of the adsorbate. The effect of contact time on the HMI adsorption by phosphogypsum was investigated for 3 h.

The optimum time for cadmium, copper, and zinc removal were determined at 20 min for Cd^{2+} and Cu^{2+} , and 30 min for Zn^{2+} (Fig. 4). The equilibrium is reached with a retention capacity $q_e = 0.73 \text{ mg g}^{-1}$ for Cd^{2+} metal ions, $q_e = 0.63 \text{ mg g}^{-1}$ for Cu^{2+} ions and $q_e = 0.56 \text{ mg g}^{-1}$ for Zn^{2+} ions. As a result of the experimental studies, it is seen that amounts of adsorbed cadmium, copper, and zinc increased with an increase in contact time up to equilibrium, but this trend was more pronounced for Cd than the other metals.

3.3. Kinetic studies of adsorption

Adsorption kinetics is used in order to explain the adsorption mechanism and adsorption characteristics. Two kinetic models were proposed in the

analysis of the sorption data of Cd^{2+} , Cu^{2+} , and Zn^{2+} onto PG: pseudo-first-order and pseudo-second-order model.

The adsorption rate constant proposed by Lagergreen [25] and Ho [26] using first-order reaction kinetic is shown below:

$$\log(q_e - q_t) = \log q_e - \left(\frac{K_1}{2.303} \right) t \quad (5)$$

where K_1 is the adsorption rate constant for the first-order adsorption, q_t is the amount of heavy metal adsorbed at time t (mg g^{-1}), and q_e is the amount of heavy metal adsorbed at equilibrium (mg g^{-1}).

Adsorption data were also evaluated according to the pseudo-second-order reaction kinetic proposed by Ho and McKay [27]. The linear form is given by:

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad (6)$$

where K_2 is the second-order reaction constant.

In order to calculate the adsorption rate constants, the first-order reaction kinetics was applied. Rate constants (K_1) were calculated from the slopes of the curves (Table 1).

Pseudo-second-order kinetic was also applied for the experimental data of each metal. The curves in the plot of t/q_t against t are linear and K_2 rate constants can be calculated from the slope of these curves (Fig. 5).

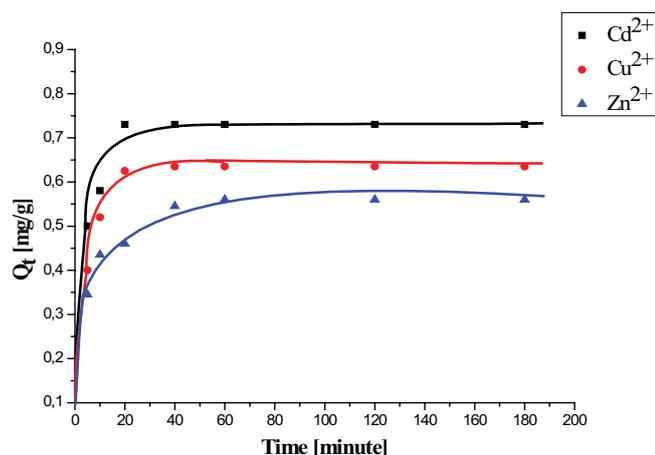


Fig. 4. Effect of contact time on adsorption of heavy metal ions by PG ($C_0 = 200 \text{ mg L}^{-1}$, $m(\text{PG}) = 2 \text{ g}$, and temperature = $25^\circ\text{C} \pm 2^\circ\text{C}$).

The values of q_e calculated are found from the intersection points of the first and second-degree reaction kinetic curves. Table 1 presents all of the data.

According to the difference between q_e calculated and q_{exp} , the kinetic model of the pseudo-first-order shows that the quantities adsorbed calculated q_e are rather low compared to the experimental quantities q_{exp} . Moreover, the kinetic model of the pseudo-first-order shows that the calculated coefficients of determination R^2 are relatively low and all the coefficients of determination of second-order reaction kinetic are higher. It is seen that the Cu^{2+} , Cd^{2+} , and Zn^{2+} removal with phosphogypsum is best described by the pseudo-second-order equation.

3.4. Effect of pH

The initial pH of metal ion solutions was changed between 2 and 12. Fig. 6 shows that the ability of phosphogypsum removal during adsorption of Cd^{2+} , Cu^{2+} , and Zn^{2+} ions depends on pH of solution.

In this study, optimal pH values for cadmium, copper, and zinc removal were determined at 9.5, 9, and 8, respectively. At high pH values, the adsorption efficiency was increased. This is due to the competitive sorption reactions between protons. It can be said that at low pH values, the H^+ ions compete with the Cd^{2+} , Cu^{2+} , and Zn^{2+} ions for the surface sites of the adsorbent. Metal adsorption in the acid range was similarly explained in the literature [28–31].

When the pH value was increased, the competing effect of H^+ ions decreased and the positively charged metal ions

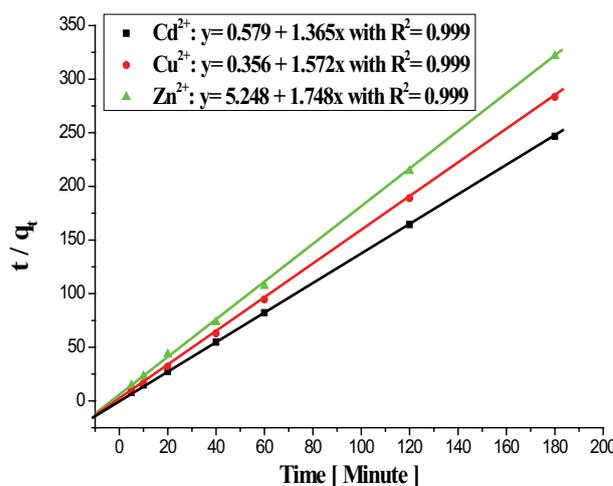


Fig. 5. Pseudo-second-order reaction kinetics for the adsorption of Cd^{2+} , Cu^{2+} , and Zn^{2+} onto PG.

hook up the free binding sites. Hence, the metal uptake was increased on the surface of the adsorbent with the increase in pH value.

The main mechanisms influencing the adsorption characteristics of phosphogypsum can be explained by ion exchange, adsorption, and precipitation. Exchangeable cations present in the phosphogypsum structure (Ca^{2+}) are exchanged for Cd^{2+} , Cu^{2+} , and Zn^{2+} cations in the aqueous solutions. In high pH level hydroxyl complexes of cadmium, copper and zinc form such as $\text{Cd}(\text{OH})^+$, $\text{Cd}(\text{OH})_2$, $\text{Cd}(\text{OH})_2(\text{s})$, $\text{Cu}_2(\text{OH})_2^{2+}$, $\text{Cu}_3(\text{OH})_4^+$, CuOH^+ , $\text{Cu}_2(\text{OH})_3^+$, $\text{Cu}(\text{OH})_2$, and ZnOH^+ , $\text{Zn}(\text{OH})_2$ may participate in the adsorption and precipitate onto phosphogypsum structure [32]. On the other hand, the precipitation of metal hydroxide into pores or spaces around the particles is hardly possible since the sorption process is kinetically faster than the precipitation [33,34].

Therefore, it can be said that Cd^{2+} , Cu^{2+} , and Zn^{2+} removal by phosphogypsum were dominantly controlled by adsorption and ion exchange at $\text{pH} < 7$ but it could be slightly enhanced by metal hydroxide precipitation at $\text{pH} > 7$.

3.5. Isotherm study

To describe the equilibrium relationships between phosphogypsum and the adsorbate of cadmium, copper, and zinc in an aqueous solution, the isothermal equations of Langmuir and Freundlich are used to explain the experimental adsorption data [35,36].

Table 1
Kinetic parameters for the adsorption of Cd^{2+} , Cu^{2+} , and Zn^{2+} onto PG

HMI	q_{exp} (mg g^{-1})	Pseudo-first-order			Pseudo-second-order		
		q_e (mg g^{-1})	K_1 (min^{-1})	R^2	q_e (mg g^{-1})	K_2 ($\text{g min}^{-1} \text{mg}^{-1}$)	R^2
Cd(II)	0.730	0.028	0.025	0.338	0.732	3.223	0.999
Cu(II)	0.635	0.208	0.026	0.477	0.636	6.944	0.999
Zn(II)	0.560	0.137	0.034	0.727	0.572	0.582	0.999

Langmuir model:

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

Freundlich model:

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \tag{8}$$

where q_m (mg g⁻¹) is the maximum adsorbed per unit mass of adsorbent, b (L mg⁻¹) is Langmuir constant that is related to the maximum adsorption capacity of HMI by adsorbent, K_f (mg g⁻¹) is the Freundlich constant that is related to adsorption capacity of HMI by adsorbent, n is the adsorption intensity, and T (K) is the absolute temperature.

Adsorption isotherms were conducted with various initial concentrations (100–500 mg L⁻¹) by adding 2 g of phosphogypsum at temperature (298 K). The curves were plotted following the models of Langmuir and Freundlich (Figs. 7 and 8):

- Evolution of $1/q_e$ vs. $1/C_e$ according to Langmuir model.
- Evolution of $\log q_e$ vs. $\log C_e$ according to Freundlich model.

Table 2 summarizes the values of the Langmuir and Freundlich constants which are calculated by linear regression from the equations related to the two models. Based on the parameters of the Langmuir and Freundlich adsorption isotherms and especially the correlation coefficients R^2 , we can say that Freundlich (Fig. 7) represents the best expression for this type of adsorption for the metal ions Cd²⁺, Cu²⁺, and Zn²⁺.

The coefficients of determination R^2 of the Freundlich model are close to 1. They indicate that more than 90% of the variability has been explained by the model. The isotherms of the adsorption of these metals on phosphogypsum can be chemical in nature for copper and cadmium because the

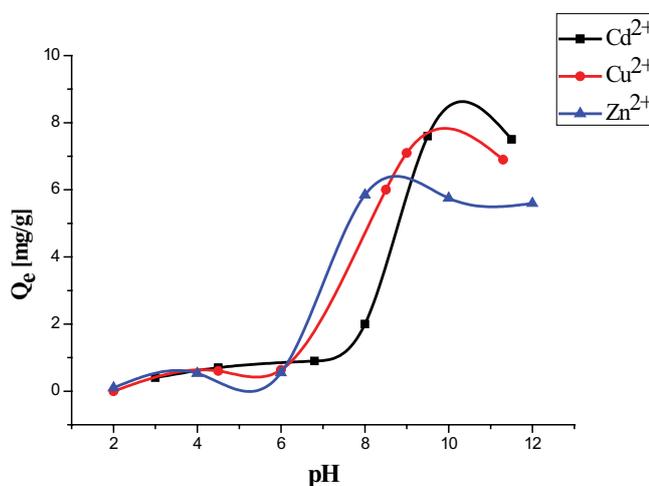


Fig. 6. Effect of initial pH on adsorption of heavy metal ions by PG ($C_0 = 200$ mg L⁻¹, temperature = 25°C ± 2°C, $m(\text{PG}) = 2$ g, and contact time = 1 h).

parameters n are greater than 1 [23,37], and $1/n$ less than 1 shows that the phosphogypsum has a heterogeneous surface with identical energy in all sites [38].

3.6. Selectivity and competitiveness potential of cadmium copper and zinc

Most of the results concerned the competitive adsorption of metals show that the adsorption of metal ions of a multi-metal ion system is lower than that obtained from a system of simple mono-metal ions of the same metal ions [39]. To evaluate this effect, the degree of competition between Cd²⁺, Cu²⁺, and Zn²⁺ ions for phosphogypsum binding sites in a mixed metal ion solution was tested. The corresponding results are illustrated in Fig. 9, which shows a small increase in Cu²⁺ ion absorption (0.63–0.67 mg g⁻¹) with equal concentrations of Cd²⁺ and Zn²⁺ ions.

In ternary metal ion mixtures, the absorption capacity of Cd²⁺ and Zn²⁺ ions decreased slightly. However, the sum of the metal ions accumulated on the sites of affinity of the phosphogypsum metal ions remains almost constant for the two studied systems (single metal systems compared to three metal ion systems).

Thus, although the phosphogypsum appears to be more selective with respect to Cd²⁺ ions during the adsorption of multiple metal ions, the existence of three metal ions Cd²⁺, Cu²⁺, and Zn²⁺ in the adsorption mixture has no effect on the overall adsorption capacity of phosphogypsum.

When the finite number of sites on phosphogypsum and the competition between metal ions for the occupation of available sites in a multi-element adsorption system are taken into account, it can be inferred that the adsorption behavior of the phosphogypsum could be influenced by the sequence in which the metal ions are introduced into the system. When metal ions are dissolved in water to form dilute solutions, they are surrounded by water molecules to create hydrated species [40]:

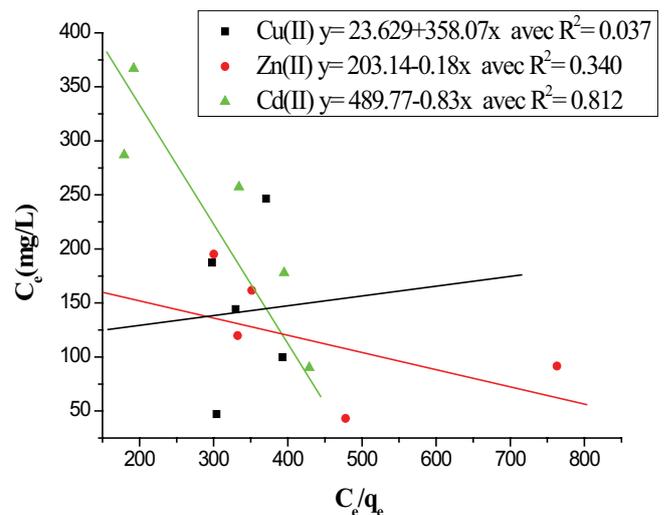


Fig. 7. Linearization of Langmuir equation in the case of studied PG/adsorbate systems.

Table 2
Parameters of the Langmuir and Freundlich isotherms for the adsorption of cadmium, copper, and zinc on phosphogypsum

Isotherms	Parameters	Phosphogypsum		
		Cadmium	Copper	Zinc
Langmuir	Q_m (mg g ⁻¹)	1.021	9.615	0.535
	b (L mg ⁻¹)	1.81×10^{-3}	3×10^{-4}	2.7×10^{-3}
	R^2	0.812	0.037	0.34
Freundlich	K_f (mg g ⁻¹)	1.32×10^{-4}	3.7×10^{-3}	4.7×10^{-4}
	n	1.610	1.0515	0.744
	R^2	0.936	0.964	0.869

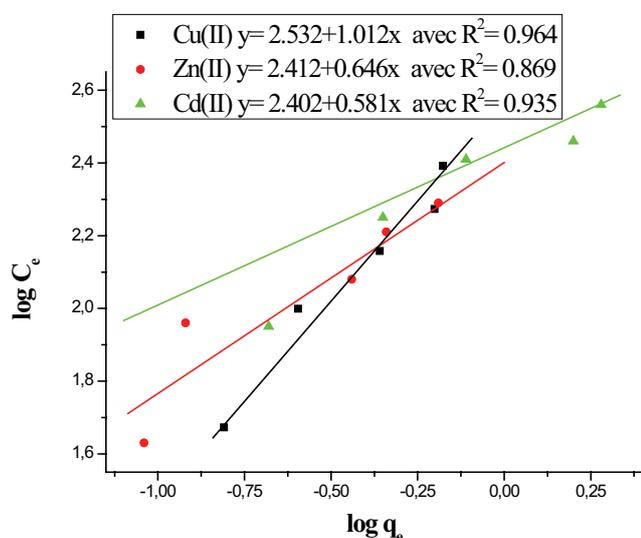


Fig. 8. Linearization of Freundlich equation in the case of studied PG/adsorbate systems.

where M^{i+} (aq) depicts the hydrated metal ion and (i) is the charge on the cation. As listed in Table 2, all three studied metal ions had the same covalent charge, with the ionic radius of Cu^{2+} and Zn^{2+} being very close to each other since these elements have atomic numbers of 29 and 30, respectively.

In simultaneous adsorption processes of the three metals cadmium, zinc, and copper, the following order of selective sorption was observed:



To explain this order, we have tried to have specific parameters for the metals involved in their ability to bind to phosphogypsum and which are represented in the following table:

The charge density is the charge density around the ion. It can be defined as the ratio of the charge of an ion to its volume or ionic radius.

$$\text{Charge density} = \frac{\text{charge of the cation}}{\text{ionic radius}} \quad (10)$$

The factors which play a role in the strength of the charge density of an ion are therefore the charge of the ion

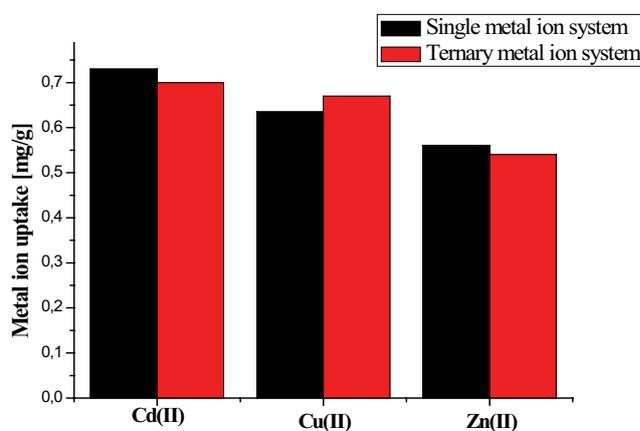


Fig. 9. Comparison of the uptake of single metal ions (metal ion concentration = 200 mg L⁻¹, pH = 5.50, $m(\text{PG}) = 2$ g, contact time = 1 h, and temperature = 25°C ± 2°C).

Table 3
Physico-chemical parameters of metal ions tested in phosphogypsum biosorption

HMI	Cd(II)	Cu(II)	Zn(II)
Atomic molar mass (g mol ⁻¹)	112.40	63.50	65.40
Atomic radius (Å)	1.71	1.57	1.53
Ionic radius (Å)	0.95	0.73	0.74
Charge	2	2	2
Charge density (Å)	2.11	2.74	2.70

(for example in our case 2+) and the effective volume on which this charge acts. This is where the ion radius or the size of the ion comes in.

Indeed, the charge density represents the attractive force of the water molecules for the cation. A high ratio, a significant attractive force reflection, indicates that the metal involved remains rather in the solvated form. In this case, the adsorption possibilities are lower compared to a metal whose ratio would be lower.

By comparing the charge density values of the three metals (Table 3), The charge density of Cd^{2+} is lower than that of Cu^{2+} and Zn^{2+} , cadmium would be better adsorbed than copper and zinc, this result is also proven experimentally (Fig. 9). For the last two metals, the result cannot be

explained by the charge density or the atomic mass but rather by the atomic radius. In fact, the atomic radius of copper is greater than that of zinc, which explains the better adsorbed quantity of copper relative to zinc.

4. Conclusion

The present study investigates the ability of phosphogypsum in adsorbing HMI from aqueous solution. Adsorption studies were carried out only with both single and ternary metal ion solutions of Cd^{2+} , Cu^{2+} , and Zn^{2+} . Infrared spectra (IR) analysis of phosphogypsum showed that after adsorption, the spectra is influenced by the adsorbed metal cations since they have a slight offset and a variation in intensity of certain vibration bands. This difference is due to the existence of exchange reactions between Ca^{2+} and Cd^{2+} , Cu^{2+} , and Zn^{2+} . The pH factor can have an important effect on the adsorption of heavy metals on phosphogypsum. The kinetic study indicates that the elimination of three metal ions with phosphogypsum is best described by the pseudo-second-order equation and the equilibrium is reached at 20 min with a retention capacity $q_e = 0.73 \text{ mg g}^{-1}$ for the metal Cd^{2+} ions, 30 min with $q_e = 0.63 \text{ mg g}^{-1}$ for Cu^{2+} ions and 30 min with $q_e = 0.56 \text{ mg g}^{-1}$ for Zn^{2+} ions. The obtained results show that the adsorption type for Cd^{2+} , Cu^{2+} , and Zn^{2+} ions can be best expressed by the Freundlich model. The phosphogypsum adsorbs Cd^{2+} ions to a greater extent than Cu^{2+} and Zn^{2+} ions in both single and multi-metal ion solutions. This result is explained by the intervention of the effect of charge density or ionic radius. In a ternary metal ion system, phosphogypsum retains their overall metal ion uptake capacity, although a slight increase in the uptake of Cu^{2+} ions and a slight reduction in the uptake of Zn^{2+} and Cd^{2+} ions occurs. The amount of Cd^{2+} , Cu^{2+} , and Zn^{2+} adsorbed onto phosphogypsum increases with the pH value and the optimum adsorptions occur at pH of basic solutions of 9.5, 9.0, and 8, respectively. Phosphogypsum can, therefore, be considered as a low-cost adsorbent for the removal of heavy metals from aqueous basic solutions, especially of cadmium ion. It is then a valuable by-product to be exploited and not waste from the phosphoric acid process.

Symbols

C_0	—	Initial concentration in aqueous solution, mg L^{-1}
C_e	—	Concentration of metal at equilibrium, mg L^{-1}
V	—	Volume of the reaction mixture, L
K_1	—	Premier-order model constant, min^{-1}
K_2	—	Second-order model constant, $\text{g mg}^{-1} \text{ min}^{-1}$
t	—	Time, min
m	—	Mass of phosphogypsum adsorbent, g
q_e	—	Amount of heavy metal adsorbed at equilibrium, mg g^{-1}
q_t	—	Amount of heavy metal adsorbed at time t , mg g^{-1}
q_m	—	Maximum adsorbed per unit mass of adsorbent, mg g^{-1}
b	—	Langmuir constant, L mg^{-1}
K_f	—	Freundlich isotherm constant, mg g^{-1}
n	—	Adsorption intensity
T	—	Absolute temperature, K

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