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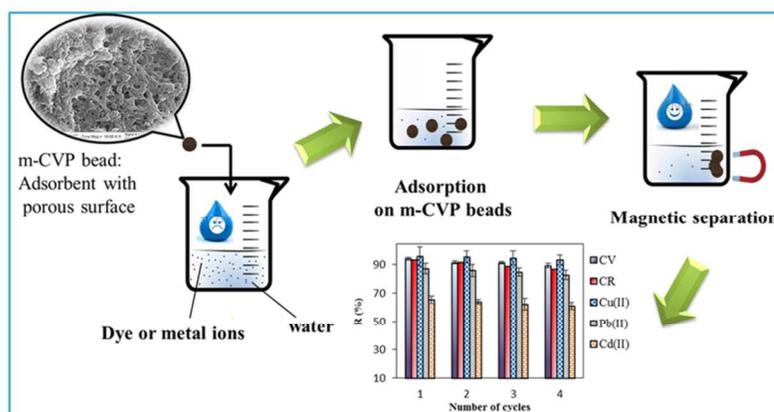
# Removal of dyes and heavy metal ions from water by magnetic hydrogel beads based on poly(vinyl alcohol)/carboxymethyl starch-g-poly(vinyl imidazole)

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Highly porous magnetic nanocomposite hydrogel (m-CVP) beads were prepared and used for the removal of dyes and heavy metal ions.



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## Removal of dyes and heavy metal ions from water by magnetic hydrogel beads based on poly(vinyl alcohol)/carboxymethyl starch-g-poly(vinyl imidazole)

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### Abstract

Novel magnetic nanocomposite hydrogel (m-CVP) beads were prepared by instantaneous gelation of carboxymethyl starch-g-polyvinyl imidazole (CMS-g-PVI), poly(vinyl alcohol) (PVA), and  $\text{Fe}_3\text{O}_4$  mixture in boric acid solution followed crosslinking by glutaraldehyde (GA). Highly porous m-CVP beads with magnetic sensitivity were fully characterized and used as eco-friendly adsorbent for removal of crystal violet (CV) and congo red (CR) dye and Pb(II), Cu(II) and Cd(II) from water. Batch adsorption results showed that the sorbent had high affinity to the heavy metals and dyes in water. The adsorption kinetics results showed that the adsorption rates could be described by pseudo-second-order kinetics indicating chemical sorption at rate determining step. Sorption of Pb(II), Cu(II), Cd(II), CR and CV to m-CVP beads agreed well to the Langmuir adsorption model at different ionic strengths with the maximum adsorption capacity of 65.00, 83.60, 53.20, 83.66 and 91.58  $\text{mg g}^{-1}$ , respectively. Positive values of  $\Delta H_0$  showed that the adsorption was chemisorption, and the negative values of  $\Delta G_0$  indicated the spontaneity of the pollutant adsorption. Desorption and reusability of m-CVP beads was also investigated for tested heavy metal ions and dyes based on sequential adsorption-desorption cycles. All the studied results indicated that m-CVP beads were an efficient, low cost, and reusable adsorbent for removal of dye and heavy metal ions from aqueous solutions.

**Keywords:** Bead, Hydrogel, adsorption, poly(vinyl alcohol), heavy metals.

## 1. Introduction

The effective treatment of chemical contaminations of water in the environment has become one of the major issues of public interest due to their toxicity. Heavy metal ions, aromatic compounds (including phenolic derivatives, and polycyclic aromatic compounds) and dyes are often found in the environment as a result of their wide industrial uses.<sup>1</sup> There are many kinds of technologies used for heavy metal and dye removal of wastewater such as membrane separation, chemical oxidation, coagulation and flocculation, photocatalytic degradation, and adsorption methods.<sup>2-6</sup> The adsorption is now the most common technology for removal of dyes and heavy metal from water due to its effectiveness, efficiency, economy and no secondary pollution. Magnetic separation is one of the promising ways for environmental purification technique because it produces no contaminants such as flocculants and it has the capability of treating large amounts of wastewater within a short time. Embedding of magnetic nanoparticles in porous polymer materials can expand the absorption capacity due to the improvement in electrostatic interaction.<sup>7</sup>

Recently, natural low cost polysaccharide materials such as starch, chitosan and gum have gained interest for application as adsorbents in wastewater treatment because of biodegradability and non-toxic nature.<sup>8-10</sup> Starch is a biodegradable agriculturally derived biopolymer with some limit properties including poor chemical stability, low mechanical strength and difficult recovery. Chemical modification of starch can greatly improve its properties. A variety of starch derivatives containing amide, amino, carboxyl and other groups have been prepared and utilized to water treatment for decades.<sup>11-13</sup> Combining two or more polymers has increasingly become an important technique for the development of new biomaterials with improved properties that could not be achieved by

individual polymers. Poly(vinyl alcohol) (PVA) is a water soluble, biodegradable and nontoxic polymer that has been used in many blend formation for biomedical<sup>8</sup> and water treatment applications.<sup>14,15</sup> PVA beads and chitosan/PVA hydrogel beads have been widely investigated as the effective adsorbents for heavy metal ions and dyes.<sup>14-18</sup> PVA/starch blend is also recognized as a potential biodegradable polymeric material.<sup>19</sup> However, study on preparation, characterization and adsorption properties of magnetic crosslinked starch/PVA hydrogel in beads form for dye and heavy metals removal has not yet been studied.

In the present study, vinyl imidazole (VI) was graft-copolymerized onto macromolecular chains of acid functionalized carboxymethyl starch (CMS) in the presence of potassium persulfate as initiator to afford water soluble CMS-g-PVI copolymer. Then, mixture of CMS-g-PVI, PVA, and Fe<sub>3</sub>O<sub>4</sub> nanoparticles was used in preparation of magnetic hydrogel nanocomposite beads (m-CVP) by instantaneous gelation method in boric acid followed crosslinking by glutaraldehyde (GA). The prepared beads were characterized by FT-IR, scanning electron microscopy (SEM), vibrating sample magnetometer (VSM), X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDX), Transmission electron microscopy (TEM) and thermal gravimetric analysis (TGA). The adsorption equilibrium of a cationic dye, crystal violet (CV), and an anionic azo dye, congo red (CR), and heavy metal ions such as Cu(II), Pb(II) and Cd(II) from aqueous solutions on m-CVP beads was investigated in detail. The effect of various parameters such as initial dye and heavy metal ion concentrations, contact time, and temperature on the adsorption was studied to investigate adsorption isotherms, kinetics and thermodynamics.

Adsorption/desorption experiments was also examined to find out the reusability of the adsorbent.

## 2. Experimental

### 2.1. Materials

Polyvinyl alcohol (PVA) was 98% hydrolyzed with a molecular weight average of 49,000 and purchased from Aldrich Chemical Company. Glutaraldehyde (GA) aqueous solution (25 wt%), starch, sodium hydroxide, monochloroacetic acid, hydrochloric acid and ammonia solution were purchased from Merck and used without further purification. 1-Vinylimidazole (VI), copper sulfate ( $\text{Cu}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$ ), cadmium chloride ( $\text{CdCl}_2 \cdot 12\text{H}_2\text{O}$ ), lead nitrate ( $\text{Pb}(\text{NO}_3)_2$ ), Ferric chloride ( $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ), and ferrous chloride ( $\text{FeCl}_2 \cdot 7\text{H}_2\text{O}$ ) were purchased from Fluka. Potassium persulfate (KPS) (Aldrich) was used as initiator for grafting of PVI onto carboxymethyl starch (CMS). Congo red (CR) and crystal violet (CV) dye were purchased from Sigma-Aldrich.

### 2.2. Preparation of carboxymethyl starch (CMS)

The experimental technique adopted for carboxymethylation of starch was as follows: 3.2 g sodium hydroxide, 4 g starch, 4 g monochloroacetic acid and 20 mL distilled water were put inside of a 100 mL flask.<sup>20</sup> The mixture was stirred with a magnet stir at 60 °C for 3 h and then was neutralized with 10 wt% acetic acid solution. The reaction product was precipitated in ethanol, filtered and then dried in a vacuum oven at 60 °C for 4 h.

### 2.3. Preparation of carboxymethyl starch-g-poly(vinyl imidazole) (CMS-g-PVI)

1 g CMS was dissolved in 50 mL distilled water in a three-necked flask and stirred magnetically for 15 min to obtain a homogeneous solution. Then 3.7 g vinyl imidazole

(VI) was added into the solution and purged with argon gas for 30 min. The temperature was raised to 60 °C and a solution of potassium persulfate (KPS) was added to the solution to initiate the graft copolymerization of VI. The reaction was preceded at 60 °C for 3 h. The reaction product was precipitated in acetone, filtered, and then extracted with hot methanol for 24 h. The synthetic procedure for preparation of CMS-g-PVI and CMS from starch is illustrated in **Fig. 1a**. The following equation was used to estimate the grafting yield:

$$\text{Grafting yield (\%)} = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

Where  $W_1$  and  $W_2$  are the weights of CMS before and after graft reaction. The grafting yield was obtained 200 % ( $\pm 15.6$ ) for PVI grafted carboxymethyl starch.

#### 2.4. Preparation of Fe<sub>3</sub>O<sub>4</sub> nanoparticles

Magnetic Fe<sub>3</sub>O<sub>4</sub> nanoparticles were prepared by conventional co-precipitation method.<sup>21</sup> FeCl<sub>3</sub>·6H<sub>2</sub>O (10 mmol, 2.730 g) and FeCl<sub>2</sub>·7H<sub>2</sub>O (5 mmol, 0.994 g) were dissolved in deionized water (20 mL) and stirred at 80 °C. Then, 80 mL of NH<sub>4</sub>OH solution (1.5 M) was added into the mixture under N<sub>2</sub> atmosphere until the pH reached 10 and the reaction mixture was stirred for 1 h. The formed black precipitate was separated by an external magnet, and then was washed several times with deionized water.

#### 2.5. Preparation of magnetic hydrogel beads

The CMS-g-PVI/PVA/ Fe<sub>3</sub>O<sub>4</sub> hydrogel beads (m-CVP) with weight ratios (w/w) of (CMS-g-PVI):(PVA):(magnetite) = 2:2:1, were prepared by instantaneous gelation method followed chemical crosslinking by GA.<sup>16</sup> First, CMS-g-PVI (2 g) was dissolved in distilled water (40 mL) and 5 wt% PVA solution was prepared by dissolving certain

amount of PVA powder in distilled water at 80 °C. Then, the PVA solution was mixed homogeneously with CMS-g-PVI solution, and then stirred vigorously with Fe<sub>3</sub>O<sub>4</sub> nanoparticles for 24 h to form gel-forming solution. After that, the mixture was dropped through a syringe needle into acetone solution of boric acid under stirring at 300 rpm where spherical beads were formed instantaneously. The beads were retained in this solution for 24 h. For chemical crosslinking, 1.5 mL glutaraldehyde and 1 mL hydrochloric acid (1M) was added to the above mixture and then incubated for 8 h at 55 °C. It is worth noting that the magnetic hydrogel beads were recovered with the help of an external magnet in order to remove unreacted chemicals. Finally, the beads were rinsed with distilled water and dried at 50 °C in vacuum oven.

## 2.6. Characterization

FT-IR spectra were recorded in the range of 400–4000 cm<sup>-1</sup> on KBr pellets using a Bruker Vector 22 FT-IR spectrophotometer (Bruker, Karlsruhe, Germany). Scanning electron microscopy (SEM) (Leo 1455 VP, Germany) was used to study the surface morphology of m-CVP beads. TEM imaging of m-CVP beads was performed using instrument (model EM10C, Zeiss Co.) with an accelerating voltage of 80 kV. A vibrating sample magnetometer (VSM) (Kavir Magnetic Co. Iran) was used to evaluate the room temperature magnetic parameter of Fe<sub>3</sub>O<sub>4</sub> and magnetic hydrogel beads with an applied field from -10000 to +10000 Oe. In VSM, the sample under study was kept in a magnetic field to be magnetized by aligning the magnetic dipoles or the individual magnetic spins of the magnetic particles along the direction of the applied magnetic field. The stronger the applied field, the larger is the magnetization. The thermal behavior of m-CVP beads was evaluated by TGA (Rheometric Scientific, USA) from room temperature up to 600

°C under nitrogen atmosphere with the heating rate of 10 °C min<sup>-1</sup>. XRD measurements were carried out using an X-ray diffractometer (XRD, GBC MMA Instrument). The patterns with the CuK<sub>α</sub> radiation (1.5418 Å) at 35.4 kV and 28 mA were recorded in the 2θ region from 10° to 80°. The Brunauer–Emmett–Teller (BET) surface area of m-CVP beads was obtained from N<sub>2</sub> adsorption isotherms at 77 K with a Micromeritic chemisorb 2750 analyzer. The mechanical stability of m-CVP beads were measured according to procedure reported in the literature.<sup>22</sup> The m-CVP beads (m<sub>1</sub>) were added to 100 mL deionized water, and after 24 h of shaking at 250 rpm in a mechanical shaker, the granules were filtered and dried at 50 °C for 24 h to obtain the remaining weight (m<sub>2</sub>). The stability of the m-CVP bead was calculated from m<sub>2</sub>/m<sub>1</sub> × 100%. The water absorption of the prepared beads was determined in distilled water from room temperature to 55 °C. The dried beads were first weighed (W<sub>0</sub>), and then were fully immersed in a beaker filled with distilled water. At regular time intervals, the beads were taken out and weighed (W<sub>1</sub>) after their surface water droplets were dried by a tissue. The absorption was calculated using equation (2):

$$\text{Swelling or deswelling(\%)} = \frac{W_1 - W_0}{W_0} \times 100 \quad (2)$$

Deswelling of the beads was also determined with variation of temperature. First, the beads were weighed (W<sub>0</sub>) and were immersed in a beaker in distilled water at 55 °C. After equilibrium, the beads were taken out, dried with a tissue and weighed (W<sub>1</sub>) and swelling was measured. Then, the beads transfer to the beaker again and temperature was decreased to 45°C, and remained at this temperature for 3 h to achieve equilibrium. The weight of sample after drying with a tissue was determined. This process was repeated at 35 °C and at 25 °C and deswelling was determined.

For determination of solubility (%), the dried beads ( $m_1$ ) were immersed in a beaker filled with distilled water. After 24 h, the beads were dried in oven at 60 °C and weighed again ( $m_2$ ). The percentage of solubility was calculated using equation (3):

$$\text{Solubility (\%)} = \frac{m_1 - m_2}{m_1} \times 100 \quad (3)$$

## 2.7. Dye and heavy metal adsorption experiments

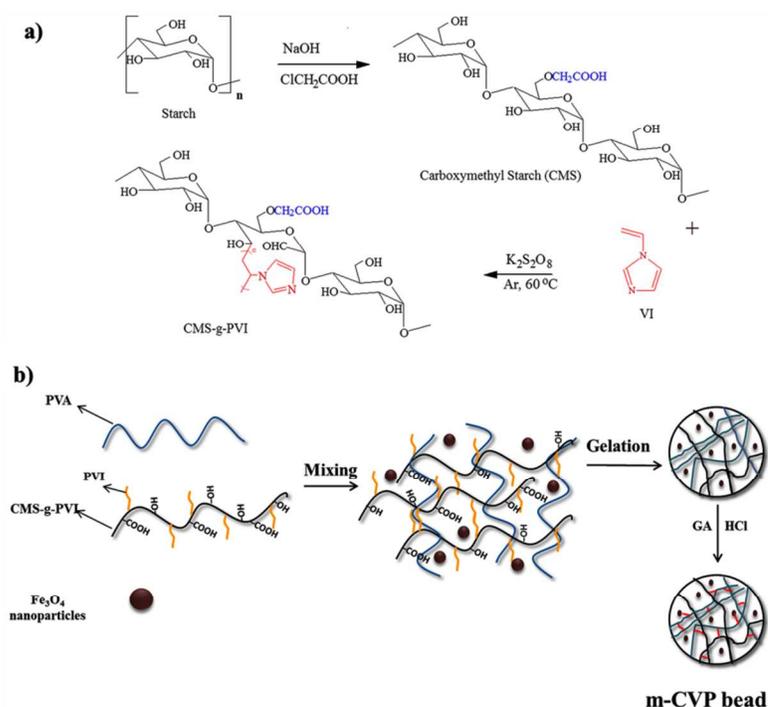
Batch experiments were conducted to study adsorption behavior of crystal violet, CV, (a cationic dye), Congo red, CR, (an anionic azo dye) and Pb(II), Cu(II) and Cd(II) heavy metal ions onto m-CVP beads in aqueous media. For determination of optimum dosage of adsorbent, the adsorption experiments were carried out by using beads in the range of 0.01- 0.1 g (0.2- 2 g L<sup>-1</sup>) in the solution of dyes and heavy metal ions (20 mg L<sup>-1</sup>), and the mixture was stirred at 200 rpm at 25 °C for a predetermined time. The effect of pH was studied in the range of 2-6 and 2-8 for heavy metal ions and dyes, respectively. The pH of the initial solution was adjusted to the required pH value using either 0.1 M HNO<sub>3</sub> or 0.1 M NaOH. Adsorption isotherms were studied with a constant dosage of beads (1 g L<sup>-1</sup>) and different initial concentrations of dye and heavy metal ions in the range of 20-200 mg L<sup>-1</sup>. Adsorption kinetics was studied at a constant concentration with changing the contact time in the range of 0.5-24 h. The effect of temperature on adsorption was carried out with 0.05 g of beads in 50 mL of dye and heavy metal ion solution (40 mg L<sup>-1</sup> concentration) at different temperatures ranged from 25 to 55 °C. In this study, Dye concentration was determined by a UV-Vis spectrophotometer at a wavelength of 590 nm, maximum absorbance, for CV and 500 nm for CR. The concentration of heavy metal ions was determined with an atomic absorption spectrophotometer (nov AA 400p,

Germany). The removal percentage ( $R$ , %) and the adsorption capacity ( $Q_e$ ,  $\text{mg g}^{-1}$ ) of the beads was calculated using the following equations

$$R(\%) = \frac{C_0 - C_e}{C_0} \times 100 \quad (4)$$

$$Q_e = \frac{(C_0 - C_e)V}{m} \quad (5)$$

where  $C_0$  and  $C_e$  ( $\text{mg L}^{-1}$ ) are the concentrations of dye and heavy metal ions in initial solution and in aqueous phase after adsorption, respectively,  $V$  is the volume the aqueous phase (L) and  $m$  is the weight of adsorbent.



**Fig. 1** Illustration of synthetic procedure for preparation of CMS and CMS-g-PVI (a), and preparation of m-CVP beads(b).

## 2.8. Desorption and reusability experiments

Desorption of CV adsorbed m-CVP beads was carried out in 100 mL ethanol for 9 h at

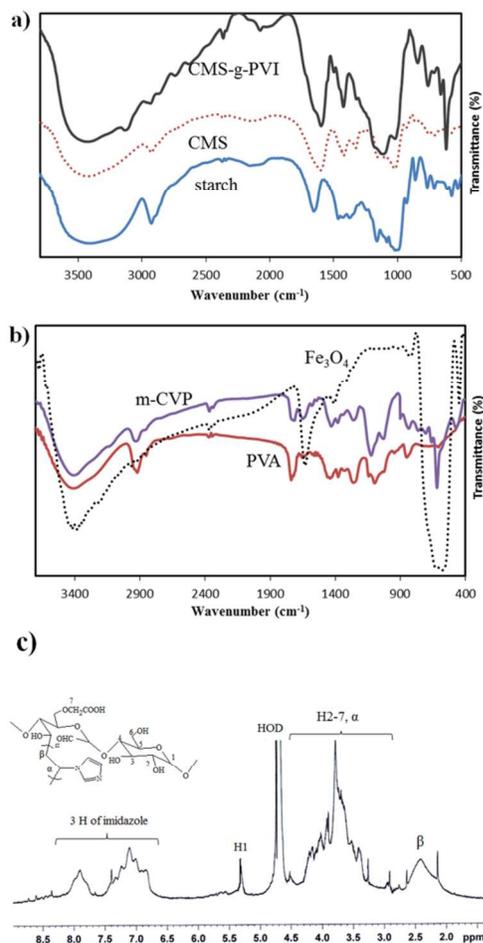
room temperature while, desorption of CR was investigated in 0.1 M NaOH solution. Desorption of heavy metal ion adsorbed m-CVP beads was carried out in 100 mL of 0.01 M HNO<sub>3</sub> solution. After removal of beads from desorption medium using external magnet, the beads were washed with distilled water and dried at 60 °C and used for the subsequent runs. The adsorption-desorption cycles were repeated four times using the same adsorbents. To measure the probable leaching of Fe from m-CVP beads, 0.05 g adsorbent was added to 100 mL of 0.01 M HNO<sub>3</sub> and the release of Fe ions was measured by atomic absorption spectrophotometer after 24, 48 and 72 h.

### 3. Results and discussion

#### 3.1. Characterization of m-CVP beads

The detailed mechanistic scheme of synthesis of magnetic nanocomposite hydrogel beads (m-CVP) is shown in **Fig. 1b**. These hydrogel beads were prepared by instantaneous gelation of mixture of PVA, CMS-g-PVI, and Fe<sub>3</sub>O<sub>4</sub> nanoparticles in boric acid solution followed crosslinking by glutaraldehyde. FT-IR spectra of m-CVP beads and the starting materials are presented in **Fig. 2a** and **2b**. The spectrum of starch and CMS discloses broad absorption bands at 3420 cm<sup>-1</sup>, due to the stretching frequency of the OH group, at 2925 cm<sup>-1</sup> due to stretching vibration of C-H, and at 1018 cm<sup>-1</sup> due to C-O-C stretching vibration. In the spectrum of CMS two strong bands are observed at 1602 and 1422 cm<sup>-1</sup> due to carboxylate group which in this case considered a clear indication that carboxymethylation of starch took place.<sup>23-25</sup> In the spectrum of poly(N-vinyl imidazole) grafted onto CMS (CMS-g-PVI), absorption bands at 3116 cm<sup>-1</sup> are attributed to the stretching vibrations of C=C-H and N=C-H in the VI ring, at 2850 and 2928 cm<sup>-1</sup> due to

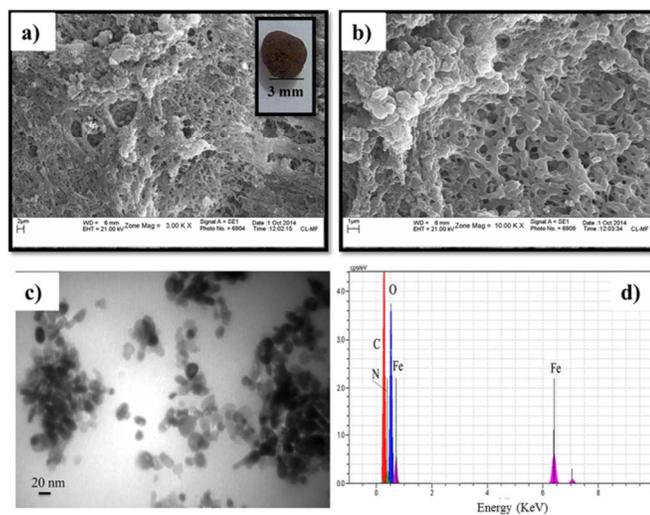
C–H stretching of CH and CH<sub>2</sub> in the main chain and at 1497 and 1544 cm<sup>-1</sup> due to C–C and N–C stretching.<sup>26</sup>



**Fig. 2** FTIR spectra of synthesized materials (panels **a** and **b**), and <sup>1</sup>H NMR of CMS-g-PVI (panel **c**).

The bands centered at 760 and 660 cm<sup>-1</sup> are assigned to C–H ring bending vibration and C–N vibration ofazole ring, respectively.<sup>27</sup> The <sup>1</sup>H NMR spectrum of the CMS-g-PVI is shown in **Fig. 2c**. The obvious signals for grafting of PVI are presented in the region of 6.8-7.9 ppm which is attributed to the hydrogen of imidazole rings. The H<sub>β</sub> in the PVI main chains is appeared at 2.4 ppm.<sup>28</sup> Signals in the region of 3.5 to 4.5 were characterized to the H<sub>α</sub> of PVI and protons of CMS.<sup>23,28</sup> The characteristic absorption

bands of PVI appeared in the FT-IR and  $^1\text{H}$  NMR spectrum of CMS-g-PVI, confirmed that PVI has been successfully grafted onto the CMS. In the FT-IR spectrum of  $\text{Fe}_3\text{O}_4$  (**Fig. 2b**), the absorption bands at around  $653\text{ cm}^{-1}$  can be ascribed to the Fe–O stretching vibration of  $\text{Fe}_3\text{O}_4$ . In addition, O–H stretching vibration around  $3420\text{ cm}^{-1}$  and O–H deformed vibration at  $1633\text{ cm}^{-1}$  suggest that surface of nanoparticles are covered with OH groups.<sup>6</sup> To verify the network structure m-CVP beads, FT-IR spectrum of as-prepared m-CVP adsorbents (**Fig. 2b**) was compared to CMS-g-PVI, PVA and  $\text{Fe}_3\text{O}_4$ . The band observed between  $3550$  and  $3200\text{ cm}^{-1}$  corresponds to the stretching of O–H from the intermolecular and intramolecular hydrogen bonds.<sup>13</sup> The characteristic absorption bands of CMS-g-PVI are observed in the spectrum of m-CVP beads. Furthermore, vibration bands of PVA and or  $\text{Fe}_3\text{O}_4$  nanoparticles have been verified in IR-spectrum of m-CVP beads.

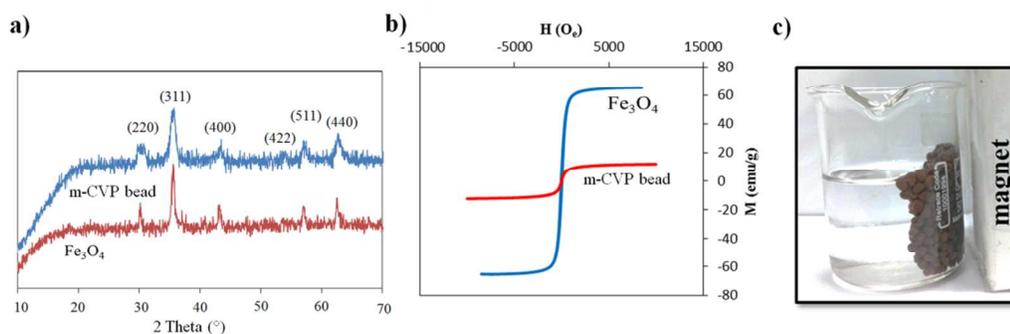


**Fig. 3** Digital photograph of a bead (right corner of panel **a**), SEM images of m-CVP beads (panel **a**: low magnification and panel **b**: high magnification), TEM image (panel **c**) and EDX patterns (panel **d**) of m-CVP beads

**Fig. 3** shows both macro and micro structures of m-CVP beads. In the right corner of **Fig.**

**3a**, a photo image of m-CVP bead is shown with nearly spherical shape and an average diameter of 3 mm. The size of the beads depends on the agitating rate. To achieve the spherical uniform m-CVP beads, the coagulation bath must be agitated in a constant rate at 300 rpm. The size of spherical beads decreases with increasing the agitating rate. SEM was used to identify the micro-structure and surface morphology of m-CVP beads. As shown in **Fig. 3a** and **3b**, m-CVP beads have high porous and rough surface. Pore distribution and porosity of the beads seems similar to the results reported by other researchers for their materials.<sup>16,22,29</sup> This porosity is indicative of magnetite nanoparticles being captured and well dispersed in spaces throughout the three-dimensional structure. The roughness of the surface should be considered as a factor providing an increase in the surface area. In addition, these pores reduce mass transfer resistance and facilitate the diffusion of metal ions and dye molecules because of high internal surface area. The measured specific surface area and average pore diameter of m-CVP beads by BET method was found to be  $9.4382 \text{ m}^2 \text{ g}^{-1}$  and 4.827 nm. The total pore volume was  $0.0114 \text{ ml g}^{-1}$ . The higher specific surface areas and lower pore size were obtained for m-CVP beads compared to value of  $3.0973 \text{ m}^2 \text{ g}^{-1}$  and 16.039 nm for  $\text{Fe}^0$ - $\text{Fe}_3\text{O}_4$  nanocomposites embedded PVA/sodium alginate beads.<sup>30</sup> The porosity based on skeletal density of  $0.5 \text{ g mL}^{-1}$  was 0.0057 per gram of sample. Although  $\text{Fe}_3\text{O}_4$  nanoparticles were not visible in SEM images, their morphology could be clearly observed in TEM image of **Fig. 3c**. It can be seen that  $\text{Fe}_3\text{O}_4$  nanoparticles are nearly spherical with an average diameter of 20 nm and are homogeneously dispersed inside polymer matrix, while some agglomeration is still observed. In addition, their existence in m-CVP beads was confirmed by EDX spectra in **Fig.3d**, where typical iron peaks were

detected. The weight percent of Fe was 19.3%. The EDX image also gives information about other elements: C, O and N. They are the main elements in the m-CVP beads and originate from PVA and CMS-g-PVI components.



**Fig. 4** XRD patterns (panel **a**), VSM curves of Fe<sub>3</sub>O<sub>4</sub> and m-CVP beads (panel **b**), and photograph image of m-CVP beads separation by an external magnetic field (panel **c**)

The crystalline structure of Fe<sub>3</sub>O<sub>4</sub> nanoparticles and m-CVP beads were shown by XRD patterns in **Fig. 4a**. The main signals of crystalline magnetic nanoparticles were recorded at  $2\theta = 30.15^\circ$ ,  $35.55^\circ$ ,  $43.1^\circ$ ,  $56.97^\circ$ , and  $62.55^\circ$ . These peaks were consistent with the results obtained by Zhou et al.<sup>16</sup> At the same time, these characteristic XRD signals have also been detected from m-CVP hydrogel beads. According to the Debye-Scherrer equation, the naked Fe<sub>3</sub>O<sub>4</sub> and Fe<sub>3</sub>O<sub>4</sub> in m-CVP beads had an average diameter of 13 nm. These results indicated that the m-CVP beads have been prepared successfully without damaging the crystal structure of Fe<sub>3</sub>O<sub>4</sub> core. The magnetic properties of Fe<sub>3</sub>O<sub>4</sub> and m-CVP were investigated by VSM and illustrated in **Fig. 4b**. It is vitally important that the sorbents should possess sufficient magnetic and superparamagnetic properties. The saturation magnetization ( $\sigma_s$ ) of m-CVP beads is (12.21 emu/g) much lower than the saturation magnetization of Fe<sub>3</sub>O<sub>4</sub> (65.43 emu/g). In spite of EDX results which showed almost 20% Fe presence in the m-CVP beads, this decrease (~80%) in  $\sigma_s$  of m-CVP

shows that Fe<sub>3</sub>O<sub>4</sub> nanoparticles were deeply covered by the polymer chains of PVA and CMS-g-PVI. Similar results have also been reported in magnetic chitosan/PVA hydrogel beads.<sup>15</sup> Furthermore, the coercivity and remanence of Fe<sub>3</sub>O<sub>4</sub> and m-CVP beads tended to zero, **Fig. 4b**, indicating the superparamagnetic properties for naked Fe<sub>3</sub>O<sub>4</sub> and m-CVP. The magnetic strength of the m-CVP beads is sufficient for separation in aqueous solution by a conventional external magnet as shown in **Fig. 4c**. The effects of cross-linker (GA) concentration on the solubility and mechanical stability of the beads are shown in **Table 1**. According to the obtained results, the solubility of the beads decreased with increasing the GA content. As can be seen in **Table 1**, when the concentration of GA is 25% of the total weight of the polymers, the beads still showed little solubility in water and 33 wt% GA was just enough to prevent the beads from dissolving in water. The m-CVP beads are water loving in nature and thus soluble in water if the crosslinking is marginal. However, they become complete water insoluble material after suitable crosslinking. Thus, the crosslinking is necessary to enhance the chemical stability of beads in aqueous medium.

**Table 1**. Effect of GA on the solubility and stability of m-CVP beads and Pb(II) adsorption

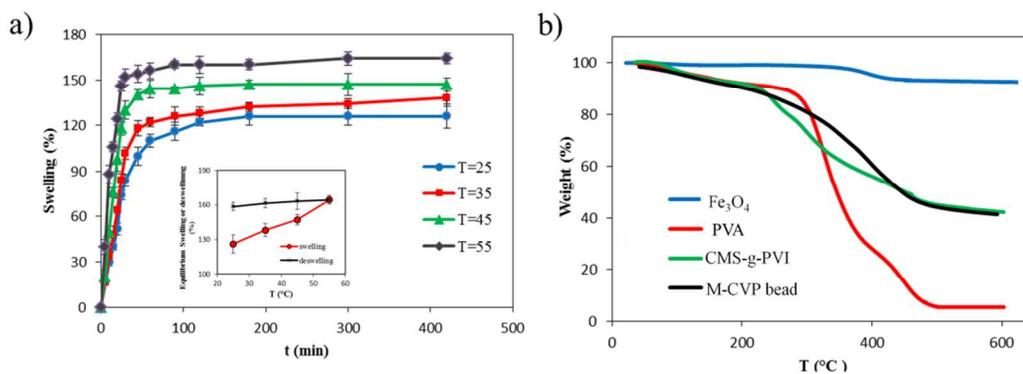
GA (%) <sup>1</sup>	Solubility (%) (STD) <sup>2</sup>	Stability (%) (STD)	Pb(II) adsorption (%) (STD)
5	66.3 (11.6)	-	-
15	19.4 (7.1)	-	-
25	5.3 (1.9)	88.2 (8.5)	90.67 (7.0)
33	insoluble	98.0 (2.5)	88.40 (5.6)
45	insoluble	99.1 (0.98)	85.5 (7.1)

<sup>1</sup>Respect to total weight of polymers

<sup>2</sup>Standard deviation

The mechanical stability of beads is affected by GA content as indicated in **Table 1**. The mechanical stability increased from 88.2 % to 99.4% when concentration of GA increased from 25 wt% to 45 wt% GA. This can be due to formation of more dense and

compact network with increasing GA content. The effect of GA concentration was also investigated on the removal percentage of Pb(II). Adsorption studies were carried out with 50 mL of 20 mg L<sup>-1</sup> Pb(II) solution containing 50 mg of the adsorbent in each case. As shown in **Table 1**, the Pb(II) adsorption has decreased with increasing the GA content. This decrease in the metal ion adsorption can be due to decrease of the number of hydroxyl groups in the polymer chains that are active in the adsorption process, and also due to compact network structure as a result of more cross-links formation. Due to the obtained results of high adsorption capacity, enough stability and insolubility, m-CVP beads with 33 wt% GA as cross-linker was used for further experiments. Therefore, these beads may also be suitable for column applications. The water absorption behavior of m-CVP beads was illustrated in **Fig. 5a**. Initially, swelling increases sharply with time up to certain level, and then it begins to level off. The equilibrium water absorption of m-CVP beads is almost 130% after ~2 h at 25 °C.



**Fig.5** Swelling behavior (panel **a**) and the inset of panel (**a**) shows the equilibrium swelling and deswelling of m-CVP beads at different temperatures, and TGA curves of Fe<sub>3</sub>O<sub>4</sub>, PVA, CMS-g-PVI and m-CVP beads (panel **b**)

The high water absorption can be due to highly porous and very hydrophilic structure of

m-CVP components. As can be seen in **Fig. 5a**, the swelling has reached at equilibrium in shorter times with increasing temperature from 25 to 55 °C. With increasing temperature, the dissociation of intermolecular interactions like hydrogen bonding between polymer chains increases water absorption. Moreover, equilibrium swelling and deswelling with temperature was shown in the inset graph of **Fig. 5a**. By decrease the temperature from 55 to 25°C, the gradual decreasing trend was observed. However, the slope of the lines of equilibrium swelling and deswelling was not the same. This shows that the absorbed water during swelling has not been removed after deswelling. The reason could be due to strong hydrogen bonding between water molecules and hydrophilic structure of the m-CVP beads which are not dissociated at the tested temperatures.

The m-CVP beads were subjected to TGA test to study its thermal stability compared with that of CMS-g-PVI, PVA and Fe<sub>3</sub>O<sub>4</sub>. In the TGA curve (**Fig. 5b**), neat Fe<sub>3</sub>O<sub>4</sub> showed a mass loss of about 2% at temperature below 150 °C due to evaporation of adsorbed moisture, and a weight loss of about 5% at temperature around 400 °C due to decomposition of Fe<sub>3</sub>O<sub>4</sub> to  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>.<sup>31</sup> The pure PVA showed mass loss of 10% below 150 °C due to evaporation of adsorbed water, and the major mass loss of ~84% occurred in the temperature range of 300-500 °C due to decomposition of polymer chain. The CMS-g-PVI copolymer also showed a 10% weight loss below 150 °C due to evaporation of adsorbed water. Thermal decomposition of this copolymer starts around 250 °C due to loss of side groups initially such as decarboxylation of CMS chains and then degradation of the main chain. However, the residue of this copolymer at 600 °C (~42%) is much higher compared to PVA indicating its higher thermal stability due to presence of aromatic imidazole rings. Based on the information shown in **Fig. 5b**, there were two

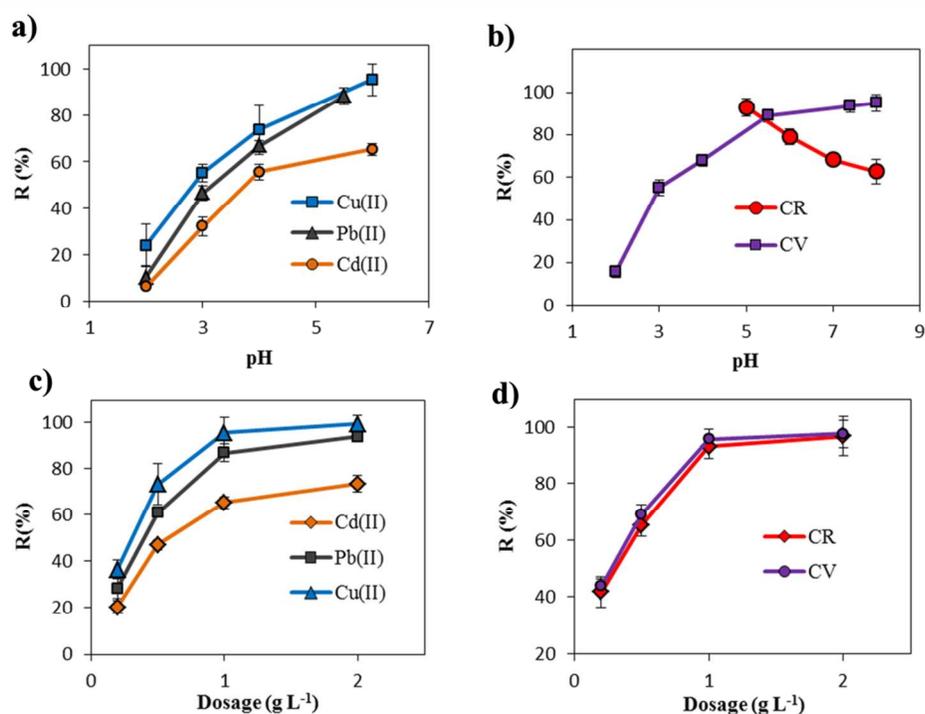
main weight loss steps in TGA curves of m-CVP beads: first step is the elimination of adsorbed water at below 160 °C, and the second step pattern with ~42% residue at 600 °C is similar to TGA curve of CMS-g-PVI copolymer, associated with degradation of PVA and CMS-g-PVI.<sup>15,16</sup> However, m-CVP beads showed higher thermal stability in the temperature range of 250-400 °C compared to CMS-g-PVI copolymer which can be due to crosslinking and network structure in m-CVP beads.

### 3.2. Adsorption of dye and heavy metal ions

#### 3.2.1. Effect of pH

The initial pH of the solution plays a key role in the adsorption process, because it influences the aqueous metal ion speciation, the adsorbent surface charge, and degree of ionization of the adsorbent during the desorption process.<sup>17</sup> **Fig. 6a,b** shows the influence of pH on adsorption of different heavy metal ions and dyes. It was found that the adsorption of Cu(II), Pb(II) and Cd(II) was highly dependent on pH because pH affected the solubility of metal ions and the ionization state of the functional group (hydroxyl and imidazole groups) present on the m-CVP beads. **Fig. 6a,b** shows that the percentage removal of metal cations and CV dye increased with increase in pH. The further increase in pH for metal ions was restricted to prevent the formation of metal hydroxide. However, in the range of pH < 4 the adsorption of Cd(II), Pb(II) and Cu(II) and CV dye decreased rapidly. This shows that acidic solution inhibit the metal cations and CV adsorption. This behavior can be explained on the basis of change in the surface charge of m-CVP beads. In acidic solution, the active groups of m-CVP such as imidazole and hydroxyl groups are protonated and competition between H<sup>+</sup> and metal ions or cationic dye for adsorption sites led to little adsorption of heavy metal ions or CV. However, with

increase of pH, deprotonation of the protonated groups takes place and m-CVP surface charge became negative which led to higher adsorption of cationic species. These results are in good agreement with those obtained for adsorption of Pb(II) on macroreticular PVA (MR-PVA) beads<sup>18</sup> and adsorption of CV onto coniferous pinus bark powder.<sup>32</sup> Therefore, solution pH were controlled at 5.5 for Pb(II), 6.0 for Cu(II) and Cd(II) and at 7.4 for CV in batch experiments. At optimum pH, the removal efficiency (%R) for Cu(II), Pb(II), Cd(II) and CV dye were 95.4%, 88.46, 65.35% and 93.66%, respectively.



**Fig.6** Effect of pH (panels **a** and **b**) and adsorbent dosage (panels **c** and **d**) on the adsorption of tested heavy metal ions and dye on the m-CVP beads

On the contrary to CV dye, the removal of CR dye by m-CVP beads increased with decreasing pH from 8 to 5, and the best result was obtained at pH=5 (it is noticeable that CR dye started to be insoluble in water and its color changed to blue at pH <5). At pH 5, the removal efficiency for CR dye was 93.11%. The CR dye has anionic sulfonate groups

in the molecule and in acidic conditions, strong electrostatic attraction between the positively charged surface of m-CVP beads and  $-\text{SO}_3^-$  groups of dye molecule led to the enhanced CR adsorption. By increasing the pH, the de-protonation of imidazole rings and hydroxyl groups in the m-CVP beads led to the decrease of CR adsorption. Similar results were observed for the adsorption of CR dye using xanthan gum/silica hybrid nanocomposite<sup>33</sup> and magnetic chitosan/poly(vinyl alcohol) hydrogel beads.<sup>15</sup>

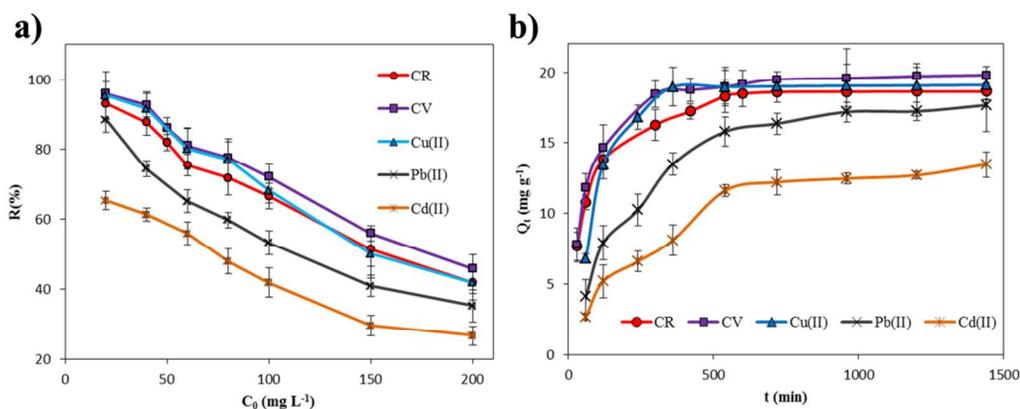
### 3.2.2. Effect of adsorbent dosage

The effect of m-CVP bead dosage ( $0.2\text{--}2\text{ g L}^{-1}$ ) on the amount of the tested metal ions and dyes ( $50\text{ mL}$ ,  $20\text{ mg L}^{-1}$ ) was studied and the obtained results are shown in **Fig. 6c,d**. The result shows that increase in adsorption was sharp with the increase in the adsorbent dosage and reached to maximum values of 73.4%, 99.3%, 93.8%, 96.7% and 97.5% for Cd(II), Cu(II), Pb(II), CR and CV pollutants, respectively at  $2\text{ g L}^{-1}$  m-CVP bead. However, saturation occurred at  $1\text{ g L}^{-1}$  at which further increase in dosage caused gradual increase on ion and dye adsorption. So,  $1\text{ g L}^{-1}$  was selected as the optimum dosage for further adsorption experiments. The increase of adsorption with increasing sorbent mass can be ascribed to the increased surface area and the availability of more adsorption sites.

### 3.2.3. Sorption isotherms

The removal percentages at different concentrations of heavy metal ions and dyes ( $20\text{--}200\text{ mg L}^{-1}$ ), keeping all other parameters constant is presented in **Fig. 7a**. As the initial concentration of Pb(II), Cu(II) and or Cd(II) heavy metal ions and CV and or CR dyes increased from  $20$  to  $200\text{ mg L}^{-1}$ , the removal percentage decreased. This reduction in adsorption efficiency can be due to the fact that the total existing adsorption sites on m-CVP beads are confined at high initial concentration, thus resulting in a decrease of percentage uptake. However, the adsorption capacity ( $Q_e, \text{mg g}^{-1}$ ) increased when their

initial concentrations have increased. The maximum adsorption capacity of Cu(II), Pb(II) and Cd(II) was determined as 83.6, 65.0, and 53.2 mg g<sup>-1</sup>, respectively. From the obtained results it was evident that Cu(II) exhibited strong affinity for m-CVP beads followed by Pb(II) and Cd(II) ions. These differences in adsorption may be related to the differences in the ionic radius and charge density. Cu(II) ions has a smaller ionic radius and greater charge density than other tested metal ions, implying that Cu(II) ion has stronger attraction to the lone pair electrons in the nitrogen and oxygen atoms to form more stable complexes. Despite of larger molecules of CR dye in comparison with the CV molecules, the active functional groups of CR for adsorption are higher than those of CV. Therefore at the optimum conditions, the maximum adsorption of CR and CV by m-CVP beads was 91.6 mg g<sup>-1</sup> and 83.7 mg g<sup>-1</sup>, respectively indicating that m-CVP beads has good potential for removal of both cationic and anionic dyes.



**Fig. 7** Effect of initial concentration of tested heavy metal ions and dyes (panel **a**), and contact time (panel **b**) on adsorption.

The adsorption isotherm studies are of fundamental importance in determining the adsorption capacity of the beads to diagnose the nature of adsorption. The adsorption isotherm experimental data were fitted by Langmuir and Freundlich models. The

Langmuir isotherm model assumes that adsorption sites are identical and energetically equivalent, and only monolayer adsorption occurs in the process.<sup>34</sup> The Langmuir equation is expressed as follow:

$$\frac{C_e}{Q_e} = \frac{C_e}{Q_m} + \frac{1}{K_L Q_m} \quad (6)$$

where  $Q_e$  ( $\text{mg g}^{-1}$ ) and  $C_e$  ( $\text{mg L}^{-1}$ ) are the adsorption capacity and the residual concentration of tested dyes or heavy metal ions in solution at equilibrium, respectively;  $Q_m$  ( $\text{mg g}^{-1}$ ) and  $K_L$  ( $\text{L mg}^{-1}$ ) are the amount of species adsorbed at complete monolayer coverage and a constant related to the affinity of the binding sites, respectively;  $Q_m$  and  $K_L$  can be determined from the linear plot of  $C_e/Q_e$  versus  $C_e$ .

The Freundlich model is an empirical equation that can be used to describe the multilayer adsorption equilibrium on heterogeneous surface.<sup>35</sup> It is mathematically described by equation (7).

$$\ln Q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (7)$$

Where  $K_F$  [ $(\text{mg g}^{-1})(\text{L mg}^{-1})^{1/n}$ ] and  $n$  are the Freundlich constants related to adsorption capacity and adsorption intensity.  $K_F$  and  $n$  can be determined from the linear plot of  $\ln Q_e$  versus  $\ln C_e$ . Experimental isotherms were determined at 25 °C and 50 mL of 1 g L<sup>-1</sup> adsorbent with different concentrations of tested dyes and heavy metal ions.

**Table 2.** Isotherm parameters for CV, CR, Cu(II), Pb(II) and Cd(II) sorption onto m-CVP beads

Pollutants	$Q_{m,\text{exp}}$ ( $\text{mg g}^{-1}$ )	Langmuir model			Freundlich model		
		$Q_{m,\text{cal}}$ ( $\text{mg g}^{-1}$ )	$K_L$	$R^2$	$K_F$	$n$	$R^2$
Cu(II)	83.60	82.21	0.149	0.995	22.85	3.39	0.9507
Pb(II)	65.00	70.92	0.074	0.9954	13.89	2.998	0.9833
Cd(II)	53.20	58.82	0.043	0.9877	7.126	2.378	0.9101
CV	91.58	96.15	0.129	0.9944	23.31	3.188	0.9681
CR	83.66	89.25	0.098	0.9945	18.84	2.981	0.9717

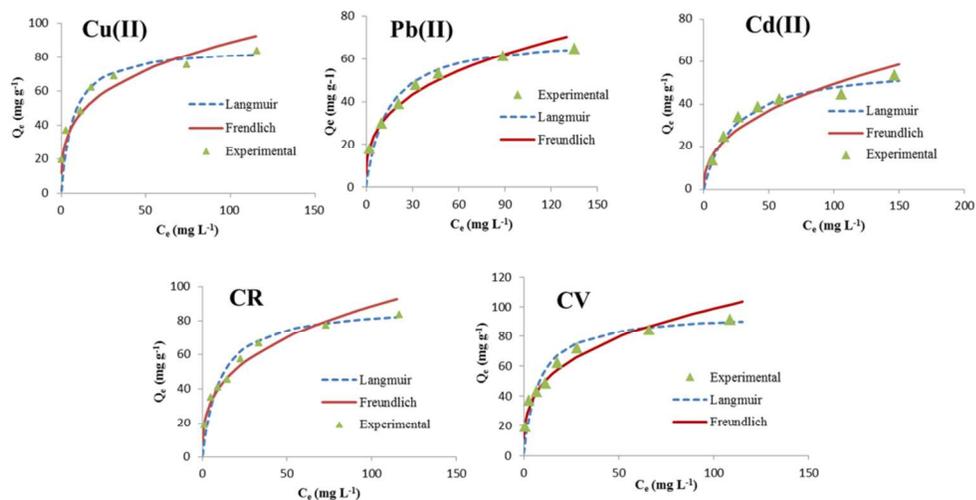
The obtained isotherm parameters,  $Q_m$ ,  $K_L$ ,  $K_F$ ,  $n$  and the correlation coefficients ( $R^2$ ) are listed in **Table 2**. The  $R^2$  of the linear form of isotherm equations for tested dyes and heavy metal ions is much closer to unity for Langmuir model than for Freundlich model (**Table 2**), and also as shown in **Fig. 8**, the experimental data is better fitted to Langmuir model. This confirms the monolayer adsorption of Cu(II), Pb(II) and Cd(II) heavy metal ions and CR and CV dye onto m-CVP beads. The theoretical monolayer capacities of m-CVP beads ( $Q_{m,cal}$ ) for selected dye and heavy metal ions were also close to that experimentally obtained (**Table 2**). The favorability of m-CVP beads as an adsorption medium for CV, CR, Cu(II), Pb(II) and Cd(II) can be obtained from the Langmuir adsorption constant  $K_L$ ; which is related to the separation factor “ $R_L$ ” defined as:<sup>36</sup>

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

where  $C_0$  is the initial concentration of pollutant. **Table 3** presents the calculated  $R_L$  values at different initial concentrations, which are in the range of 0.04-0.28 for CV, 0.06-0.33 for CR dye and in the range of 0.04-0.25 for Cu(II), 0.06-0.40 for Pb(II) and 0.13-0.54 for Cd(II) adsorption on m-CVP beads.  $0 < R_L < 1$  indicates that m-CVP beads are favorable medium for the adsorption of selected dyes and heavy metal ions. The results in **Table 2** also indicate that the equilibrium data is not fitted well with the Freundlich isotherm model (lower  $R^2$  value).

**Table 3.** Calculated  $R_L$  values at different initial concentrations of tested dyes and metal ions

$C_0$ (mg L <sup>-1</sup> )	$R_L$				
	Cu(II)	Pb(II)	Cd(II)	CV	CR
20	0.25	0.40	0.54	0.28	0.33
40	0.14	0.25	0.37	0.16	0.20
60	0.12	0.18	0.32	0.11	0.16
80	0.10	0.14	0.28	0.09	0.14
100	0.08	0.12	0.22	0.07	0.11
150	0.06	0.08	0.19	0.05	0.09
200	0.04	0.06	0.13	0.04	0.06



**Fig. 8** The adsorption isotherms of tested metal ions and dyes ( $C_0=20-200 \text{ mg L}^{-1}$ , adsorbent dosage= $1 \text{ g L}^{-1}$ ,  $T=25 \text{ }^\circ\text{C}$ , contact time = $24 \text{ h}$ )

**Table 4.** Comparison of CV, CR, Cu(II), Pb(II) and Cd(II) adsorption capacity on m-CVP beads with other adsorbents

adsorbent	$Q_m(\text{mg g}^{-1})$					Ref.
	CV	CR	Cu(II)	Pb(II)	Cd(II)	
Magnetic starch-graft-poly(acrylic acid) nanocomposite hydrogels	80.64					7
Coniferous pinus bark powder (CPBP)	32.78					32
Treated ginger waste (TGW)	64.93					37
$\text{N}_2\text{O}$ -carboxymethyl-chitosan/montmorillonite		74.24				38
chitosan/montmorillonite nanocomposite		54.52				39
xanthan gum/silica hybrid nanocomposite		209.20				33
Wool graft polyacrylamidoxime				23.56	12.55	40
Sporopollenin			17.4	94.7	7.09	41
Modified ABS			56.18	56.50	53.47	42
poly(vinylalcohol)/chitosan beads			98.77	98.61	70.16	43
Clay (montmorillonite)				31.1	30.7	44
chitosan-poly(vinyl alcohol) hydrogel			78.68	13.6	32.12	45
adsorbent						
m-CVP beads (our study)	91.58	93.66	83.60	65.00	53.2	-

The adsorption capacity ( $Q_m$ ) for CV and CR dye and Cu(II), Pb(II) and Cd(II) ions on m-CVP beads were compared with those of other low cost adsorbents found in literatures (**Table 4**). It is obvious that the m-CVP beads have good adsorption capacity when compared with other adsorbents reported previously. Therefore, it can be concluded that m-CVP beads have a good potential for removal of cationic and anionic azo dyes and heavy metal ions from aqueous solutions.

#### 3.2.4. Sorption kinetics

In order to evaluate the adsorptive property of m-CVP beads, it is important to investigate the rate at which CV, CR, Cu(II), Pb(II) or Cd(II) is removed from aqueous solution. **Fig. 7b** shows the effect of contact time (0.5-24 h) on the adsorption capacity of m-CVP beads, the initial concentration of the tested dyes and metal ions was 20 mg L<sup>-1</sup>.

Experimental results indicated that adsorption capacity of m-CVP beads increased with increasing contact time and equilibrium was reached after about 5 and 9 h for CV and CR dyes, 6 h for Cu(II) and 9 h for other tested heavy metal cations (Pb(II) and Cd(II)). Beyond these times little changes were occurred in adsorption. The equilibrium adsorption capacity was about 19.80 and 18.62 mg g<sup>-1</sup> for CV and CR adsorption and 19.08, 17.66 and 13.07 for Cu(II), Pb(II) and Cd(II) adsorption on m-CVP beads after 24 h, respectively. The adsorption process consists of two stages: rapid stage at initial time of adsorption and a slow process as the second stage. Adsorption was fast initially because of high concentration of ions and also high number of free adsorptive sites. At a later stage, adsorption slowed down and reached an equilibrium level because of a decrease in the concentration and also exhaustion of free adsorptive sites. Also, Zhu et

al.<sup>15</sup> found similar results when used magnetic chitosan/poly(vinyl alcohol) hydrogel beads to remove Congo red from aqueous solution. It is well known that different kinds of mechanisms such as chemical reaction and mass transfer can control the absorption process. In order to investigate the mechanism controlling the adsorption process (physical or chemical mechanism), the commonly used kinetic models including the pseudo-first order Eq. (9), pseudo-second order Eq. (10), and intra-particle diffusion model Eq. 11 were employed to evaluate the kinetics data. The pseudo-first order (the most reliable kinetics equation suitable only for the rapid initial phase, Eq. (9)) and pseudo-second order (for predicting the kinetic behavior of chemical sorption as a rate controlling step, Eq. (10)) models are expressed as:

$$\log(Q_e - Q_t) = \log Q_e - \frac{K_1 t}{2.303} \quad (9)$$

$$\frac{t}{Q_t} = \frac{1}{K_2 Q_e^2} + \frac{1}{Q_e} t \quad (10)$$

Where the  $Q_e$  and  $Q_t$  are the adsorption capacity ( $\text{mg g}^{-1}$ ) on the beads at the equilibrium and at time  $t$ , respectively;  $K_1$  ( $\text{min}^{-1}$ ) and  $K_2$  ( $\text{g mg}^{-1} \text{min}^{-1}$ ) are the rate constants of the pseudo-first order and the pseudo-second order adsorption, respectively, which can be obtain from  $\log(Q_e - Q_t)$  versus  $t$  and  $t/Q_t$  versus  $t$ .<sup>23,37</sup> Additionally, the initial adsorption rate,  $h$  ( $\text{mg}/(\text{g min})$ ) can be determined from  $K_2$  and  $Q_e$  values using  $h = K_2 Q_e^2$ . Intra-particle diffusion equation assumes that binding of contamination to the surface of adsorbent is influenced by the mass transfer resistance and is described as:

$$Q_t = k_{id} t^{0.5} + C \quad (11)$$

Where  $C$  is intercept ( $\text{mg g}^{-1}$ ) and  $k_{id}$  ( $\text{mg g}^{-1} \text{min}^{-1.5}$ ) is the Intra-particle diffusion rate constant, which can be evaluated from the slop of the linear plot of  $Q_t$  versus  $t^{0.5}$ . The experimental data has been fitted to the kinetics models mentioned above. The pseudo-

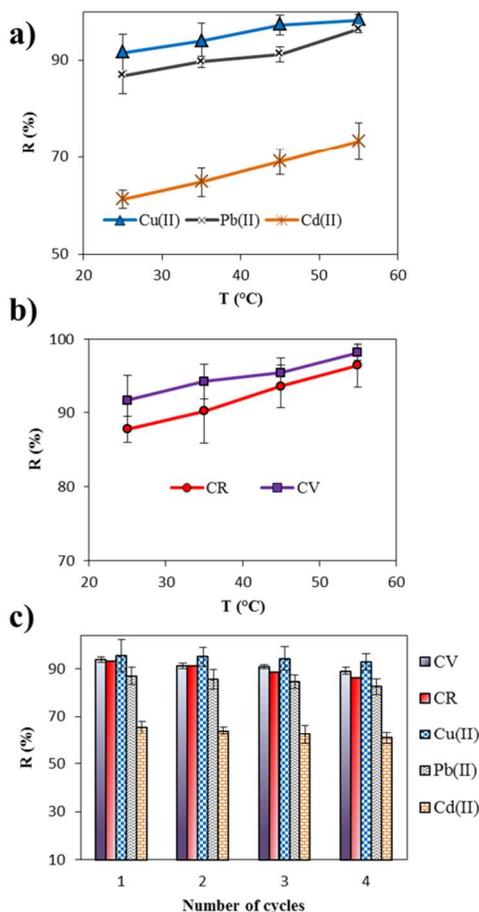
first order constants ( $Q_e$ ,  $K_1$  and  $R^2$ ) for tested dye and metal ion adsorption on m-CVP beads were presented in **Table 5**. The theoretical  $Q_e$  values calculated from the first-order kinetic model ( $Q_{e1,cal}$ ) did not agree with the experimental values ( $Q_{e,exp}$ ), and the correlation coefficients were also found to be slightly lower. These results indicated that the pseudo-first order kinetic model was not appropriate for modeling the adsorption of CV and CR dye and Cu(II), Pb(II) and Cd(II) metal ions on m-CVP beads.

**Table 5.** Kinetic parameters of CV, CR, Cu(II), Pb(II) and Cd(II) adsorption onto m-CVP beads

Kinetic model	Parameters	CV	CR	Cu(II)	Pb(II)	Cd(II)
Pseudo-first-order	$Q_{e1,cal}$ (mg g <sup>-1</sup> )	8.23	14.36	6.08	13.98	11.56
	$K_1$ (min <sup>-1</sup> )	0.0041	0.0074	0.3530	0.0032	0.0030
	$R^2$	0.9614	0.9777	0.8573	0.9703	0.9558
Pseudo-second-order	$Q_{e2,cal}$ (mg g <sup>-1</sup> )	20.44	19.38	20.12	20.41	15.90
	$Q_{e,exp}$ (mg g <sup>-1</sup> )	19.80	18.62	19.08	17.66	13.07
	$K_2$ (g mg <sup>-1</sup> min <sup>-1</sup> )	0.0012	0.0011	0.0008	0.0002	0.0002
	$h$ (mg g <sup>-1</sup> min <sup>-1</sup> )	0.4704	0.4047	0.3138	0.0624	0.0381
	$R^2$	0.9999	0.9995	0.9966	0.9964	0.9890
Intra-particle diffusion	$k_{id}$ (mg g <sup>-1</sup> min <sup>-1.5</sup> )	0.3184	0.3078	0.3057	0.4295	0.3485
	$C$ (mg g <sup>-1</sup> )	10.153	9.3648	9.7809	3.4592	1.3802
	$R^2$	0.7310	0.7676	0.5879	0.8725	0.9012

According to the results listed in **Table 5**, the values of  $R^2$  for the pseudo-second-order kinetic model were much closer to unity for m-CVP beads as adsorbent. The adsorption capacities calculated from the pseudo-second-order model ( $Q_{e2,cal}$ ) were also close to those determined by experiments ( $Q_{e,exp}$ ). The pseudo-second-order model is based on the assumption that the rate-determining step may be a chemical sorption involving valence forces through sharing or exchange of electrons between adsorbent and sorbate.<sup>42,46</sup> The  $h$  and  $K_2$  values calculated from the pseudo-second-order kinetic model were higher for CV than those obtained for CR dye, and for heavy metal ions Cu(II) had the highest value. This indicated that the adsorption of CV and Cu(II) onto m-CVP beads

was much faster than adsorption of CR and Pb(II) or Cd(II) ions. Among the mentioned models, the intra-particle diffusion model showed a poor fit to the experimental data, revealing that the intra-particle diffusion was not the rate-limiting step in the adsorption.



**Fig. 9** Effect of adsorption temperature on tested heavy metal ion and dye removal (panels **a** and **b**), and reusability of m-CVP beads during four cycles (panel **c**).

### 3.2.5. Adsorption thermodynamics

For investigating the effect of temperature, adsorption experiments were performed at 25, 35, 45 and 55 °C using 50 mL of 40 mg L<sup>-1</sup> pollutant solution. The results (**Fig. 9a, b**) showed that the removal and sorption capacity increased with increasing temperature.

This may be due to the increase in mobility of the large dye molecules and heavy metal ions with temperature. As the temperature increases, the number of molecules which require sufficient energy to undergo an interaction with active sites at the surface also increases.<sup>47,48</sup> Furthermore, according to **Fig. 5a**, increasing temperature produced a swelling effect within the internal structure of the adsorbent enabling more dye and metal ions to penetrate further. Increase of adsorption due to temperature indicates that the adsorption process was endothermic in nature. Similar endothermic nature of adsorption was observed by using magnetic chitosan/poly(vinyl alcohol) hydrogel beads.<sup>15</sup> The thermodynamic parameters such as Gibbs free energy change ( $\Delta G^0$ ), standard enthalpy change ( $\Delta H^0$ ), and standard entropy change ( $\Delta S^0$ ) were also studied to understand better the effect of temperature on the adsorption.<sup>41</sup> Gibbs free energy ( $\Delta G^0$ ) is calculated by using equilibrium constant ( $K_L$ ) from equation (12).

$$\Delta G_0 = -RT \ln K_L \quad (12)$$

$\Delta H^0$  and  $\Delta S^0$  of adsorption can be estimated from Van't Hoff equation (Eq. 13).

$$\ln K_L = -\frac{\Delta H_0}{RT} + \frac{\Delta S_0}{R} \quad (13)$$

Where  $K_L$  is the ratio of concentration of CV, CR, Cu(II), Pb(II) or Cd(II) adsorbed by the absorbent to their remaining concentration in solution at equilibrium ( $C_e$ ). The slope and intercept of the plot of  $\ln K_L$  versus  $1/T$  give  $\Delta H^0$  and  $\Delta S^0$ , respectively, and the obtained data are listed in **Table 6**.  $\Delta G^0$  values found here are negative for adsorption of the tested dyes and metal ions on m-CVP beads (**Table 6**). This indicates that the adsorption process is thermodynamically feasible and spontaneous at room temperature. Moreover, the  $\Delta G^0$  values decreased with an increase in temperature, indicating an increased trend in the degree of spontaneity and feasibility of adsorption of the dyes or

metal cations onto m-CVP beads. Generally, the change in adsorption enthalpy for chemisorption is in the range of 5.0- 100.0 Kcal mol<sup>-1</sup> (20.9-418.4 kJ mol<sup>-1</sup>).<sup>39</sup> The adsorption enthalpy change ( $\Delta H^0$ ) was calculated to be 36.48, 35.54 kJ mol<sup>-1</sup> for CV and CR dyes and 47.25, 36.85 and 14.90 kJ mol<sup>-1</sup> for Cu (II), Pb(II) and Cd(II) adsorption onto m-CVP beads, respectively. The positive values of the change in enthalpy suggest that the adsorption is chemisorption in nature. Furthermore, positive  $\Delta S^0$  of adsorption process indicates an irregular increase of the randomness at the m-CVP bead-solution interface during adsorption.

**Table 6.** Thermodynamic parameters for adsorption of CV, CR, Cu(II), Pb(II) and Cd(II) on m-CVP beads

Pollutants	$\Delta H^0$ (KJ mol <sup>-1</sup> )	$\Delta S^0$ (J mol <sup>-1</sup> K <sup>-1</sup> )	$-\Delta G^0$ (KJ mol <sup>-1</sup> )			
			25 °C	35 °C	45 °C	55 °C
Cu(II)	47.252	177.695	5.937	7.023	9.451	11.064
Pb(II)	36.855	137.913	4.518	5.558	6.200	8.973
Cd(II)	14.903	53.683	1.139	1.582	2.121	2.757
CV	36.476	142.718	6.283	7.465	8.163	10.871
CR	35.540	134.753	4.870	5.676	7.064	8.945

### 3.2.6. Reusability of adsorbents

The reusability of adsorbents after a particular process is one of the most important properties for environmental and economic reasons. Therefore the desorption-adsorption cycles were performed to investigate the potential of m-CVP beads for applications. In this study, ethanol and alkaline environment (0.1 M sodium hydroxide) solution were used as desorption media for CV and CR dye, respectively. Desorption of adsorbed Cu(II), Pb(II) and Cd(II) was carried out using nitric acid solution and the reusability was evaluated for four times as shown in **Fig. 9c**. It can be found from this figure that percentage removal of pollutants was not much affected. Therefore, m-CVP beads can be used several times for water pollution remediation. The leaching of Fe ions from m-CVP

beads after several reuse in 100 mL of 0.01 M HNO<sub>3</sub> solutions was investigated. The amount of released Fe ions was only  $2.823 \pm 0.121$ ,  $4.831 \pm 0.369$  and  $5.345 \pm 0.350$  mg L<sup>-1</sup> after 24, 48 and 72 h exposure, respectively. Moreover, the feasibility of recycling of m-CVP beads from wastewater using a magnetic field, as shown in **Fig. 4c** can prevent the secondary pollution in wastewater treatment. These results indicate that m-CVP beads are suitable for dye and heavy metal ion removal from wastewater for the industrial applications.

#### 4. Conclusions

Novel magnetic nanocomposite hydrogel (m-CVP) beads were prepared by instantaneous gelation of carboxymethyl starch-g-polyvinyl imidazole (CMS-g-PVI), poly(vinyl alcohol) (PVA), and Fe<sub>3</sub>O<sub>4</sub> mixture in boric acid followed crosslinking by glutaraldehyde (GA). The characterization of m-CVP beads indicated that Fe<sub>3</sub>O<sub>4</sub> nanoparticles have been introduced successfully in the crosslinked hydrogel beads. The saturation magnetization of m-CVP beads was enough for separation of adsorbent from solution after adsorption. The adsorption of CR and CV dye or Cu(II), Pb(II) and Cd(II) ions onto m-CVP agreed well with the pseudo second order kinetic model. The chemisorption process was spontaneous and endothermic. The experimental adsorption isotherm data were fitted with Langmuir model with maximum adsorption capacity of 91.58 and 83.66 mg g<sup>-1</sup> for CV and CR dye and 83.60, 65.00, and 53.20 mg g<sup>-1</sup> for Cu(II), Pb(II) and Cd(II) adsorbed m-CVP beads, respectively. This work will be helpful in the development of high capacity magnetic bioadsorbent with convenient recovery.

#### Notes and References

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