Application of Fe-Cu binary oxide nanoparticles for the removal of hexavalent chromium from aqueous solution
Saif Ullah Khan, Rumman Zaidi, Saeikh Z. Hassan, I. H. Farooqi and Ameer Azam

ABSTRACT

The adsorption process has been used as an effective technique for the removal of metal ions from aqueous solutions. Groundwater remediation by nanoparticles has received interest in recent years. In the present study, a binary metal oxide of Fe-Cu was prepared and used for the removal of hexavalent chromium from aqueous solution. Batch experiments were performed to investigate the effects of initial Cr (VI) concentration, dose of adsorbent, and pH of solution on the removal efficiency of Cr (VI). The prepared nanostructured Fe-Cu binary oxides were able to reduce the concentration of Cr (VI) in aqueous solution. Binary metal oxides nanoparticle exhibited an outstanding ability to remove Cr (VI) due to high surface area, low particle size, and high inherent activity. The percentage removal efficiency of Cr (VI) increased with nanoparticles doses (0.1 g L\(^{-1}\)–2.5 g L\(^{-1}\)), whereas it decreased with initial Cr (VI) concentration (1 mg L\(^{-1}\)–25 mg L\(^{-1}\)) and with pH (3–9). The Freundlich model was found to be the better fit for adsorption isotherm. The prepared nanomaterial was characterized using powder X-ray diffraction, scanning electron microscopy (SEM), and ultraviolet (UV)-visible spectroscopy. It showed that the Fe-Cu binary oxides were formed in single phase. SEM micrograph showed aggregates with many nano-sized particles. UV-visible spectroscopy showed quantum confinement effect.

Key words | adsorption, bimetallic, binary oxide, groundwater, hexavalent chromium

INTRODUCTION

Heavy metals are the main pollutants discharged to the environment as a result of industrial activities. The increasing contamination of groundwater by toxic metal ions is a significant environmental hazard to drinking water supplies. High toxicity of these metals causes serious problems to the ecosystem even at low concentrations (Luo et al. 2015). Chromium (Cr) is one of the most widely used heavy metal that has many applications in the metal cleaning and plating baths, painting, tannery and fertilizer industries (Lv et al. 2012). Chromium essentially exists in two oxidation forms namely Cr (III) and Cr (VI). Over a narrow concentration range, Cr (III) is proved to be biologically essential to mammals as it maintains an effective glucose, lipid, and protein metabolism, whereas Cr (VI) is reported to have a toxic effect on humans and it is considered to be genotoxic and carcinogenic in nature (Cheuhan & Sankararamakrishnan 2011). Moreover, Cr (VI) has been classified as a potential mutagen and teratogen and has acute toxicity for different biological systems. According to the Bureau of Indian Standards’ desirable limit for drinking water, the maximum acceptable limit for Cr (VI) is 0.05 mg L\(^{-1}\).

The different methods such as membrane filtration, electrochemical precipitation, ion exchange, adsorption, reduction of Cr (VI) to Cr (III), reverse osmosis, evaporation, chelating, solvent extraction, electrolysis, and cyanide treatment are employed for the removal of Cr (VI) from water and wastewater (Lv et al. 2012; Luo et al. 2013; Jung et al. 2013). Most of these methods have some drawbacks such as low efficiency, high demand for energy, high cost, requiring special chemicals, and the problems related to the disposal of sludge (Vaiopoulou & Gikas 2012; Jung et al. 2013). Regarding biological treatment, bioremediation by the strains of bacteria can effectively degrade Cr (VI) and is economically favourable, but the presence of bactericidal toxicants at many waste sites would limit their growth and effectiveness (Chen & Hao 1998). Chemical reduction is
known to remove Cr (VI) effectively using reducing agents such as ferrous sulfate, sulfur dioxide, or sodium bisulfate followed by precipitation as Cr (III), but the disadvantage is of being high cost and complications (Guha & Bhargava 2005).

Recently, Cr(VI) removal has been reported using a number of adsorbents such as starch functionalized magnetic nanoparticles (Singh et al. 2015), Ni2O3 nanoparticles (Dey et al. 2013), nanosized ferric oxyhydroxide-loaded anion exchanger (Li et al. 2014a), porous α-Fe2O3/Fe3O4/C (Zhu et al. 2014), alginite-montmorillonite/polyaniline nanocomposites (Olad & Azhar 2014), magnetic graphene oxide nanocomposites (Li et al. 2014b), Tunisian clay (Ghrab et al. 2014), acidic chloride media using solvent impregnated resin (Nguyen et al. 2014), amine functionalized natural and acid activated sepiolites (Marjanovic et al. 2013), chitosan and single/multi-walled carbon nanotubes (Jung et al. 2015), polyacrylonitrile/polypyrrole core/shell nanofibre (Wang et al. 2015). These recently reported Cr (VI) removal adsorbents have an advantage in terms of maximum adsorption capacities over their conventionally used counterparts such as iron, iron oxide, iron coated sand, and iron coated activated carbon which are less efficient and sludge producing (Petruševski et al. 2000). Binary metal oxides of iron and granular ferric hydroxides have also been investigated in the past (Driehaus & Jekel 1998). However, their use is limited due to high operation cost, sludge formation, and technical difficulties in preparation of materials. Recently, development of adsorbent materials based on two or more metal oxides has gained attention for removing heavy metals from wastewater since the binary not only inherits the advantages of parent oxides but also shows obviously synergistic influence. Arsenic and chromium in groundwater can be removed using nanomaterials and, currently, a lot of research is being conducted in this field. In an earlier research study, it was reported that chromium and arsenic could form a monodentate complex, a bidentate-binuclear complex, and a bidentate-mononuclear complex with iron oxides (Fendorf et al. 1997). Fendorf et al. (1997) noted that extended X-ray absorption fine structure spectroscopy provide direct evidence for inner sphere adsorption of arsenate and chromate on goethite. In acidic pH range, most arsenic and chromium species in aqueous solution are negatively charged. Thus, electrostatic attraction between magnetite-maghemite nanoparticles and metal species leads to the removal of arsenic and chromium compounds from aqueous solution. According to a previous research study carried out, adsorption of chromium (VI) by magnetite was a combination of electrostatic attraction and ligand exchange at various pH conditions (Hu et al. 2004). Many of these researches carried out in the past suggested that electrostatic attraction is the key mechanism of arsenic and chromium removal by maghemite from aqueous solutions and that the process is highly dependent on initial concentration, pH, and temperature (Hu et al. 2005). Previous studies have also shown competitive adsorption of arsenic or chromium with other anions (for example, phosphate and sulphate). The presence of orthophosphate prevented the adsorption of chromium (VI), most likely due to competition for adsorption sites. Consistent with this finding, KH2PO4 was found to be the best extracting agent for chromium (VI) (Bartlett & Kimble 1976). The existence of phosphate (P) or organic ligands not only competes with solution chromium (VI) for surface sites, but also results in releasing adsorbed chromium (VI).

Fe0 nanoparticles have long been used in the electronic and chemical industries due to their magnetic and catalytic properties. Fe0 nanoparticles having large surface area further fosters enhanced reactivity for the transformation of the recalcitrant environmental pollutants. The Fe0 nanoparticle is a strong reducer and it has been used to remove heavy metals (Buege & Hug 1999; Puls et al. 1999; Ponder et al. 2000; Biterna et al. 2010). It is generally accepted that nano Fe0 has a core–shell structure with a Fe0 core surrounded by an oxide/hydroxide shell, which grows thicker with the progress of iron oxidation (Li & Zhang 2006, 2007). In earlier research, oxide layer thickness was determined in core–shell Fe0 nanoparticles by using high resolution transmission electron microscopy and high resolution X-ray photo electron spectroscopy and the values were in the range of 2–4 nm (Martin et al. 2008). As compared with the single metal oxides of iron, the binary metal oxides of iron show higher performance for removing arsenic, chromium, and phosphates from contaminated water.

MATERIALS AND METHODS

All chemicals used in this work were of analytical grade (>95% purity) and provided by Merck (Merck, Darmstadt, Germany). Stock solution (1,000 mg L−1) of Cr (VI) was prepared by dissolving 2.829 g of K2Cr2O7 in 1,000 mL of Milli-Q water and further diluted to prepare the solutions in the concentration range of 1−25 mg L−1. Standard acid (0.1 M HNO3) and base (0.1 M NaOH) solutions were used for pH adjustment. Atomic absorption spectrometer (PinAAcle
900F AAS) was used to measure Cr (VI) concentrations in the filtrate.

In the present study, an attempt was made to prepare a binary oxide of iron-copper by a simple co-precipitation method at room temperature. The main objective of our study was to propose a facile co-precipitation method for the synthesis of Fe-Cu binary oxide at room temperature; second was to characterize the prepared material with different techniques, and finally was to evaluate chromium adsorption capacity of iron-copper binary oxides as well as the effect of pH of the solution on adsorption capacity of the prepared material.

**Preparation of Fe-Cu binary oxide**

The Fe-Cu binary oxides were prepared in the molar concentration of 1:2 at room temperature. In a typical synthesis method, a certain amount of ferric chloride hexahydrate (FeCl₃·6H₂O) and copper (II) sulphate pentahydrate (CuSO₄·5H₂O) were taken in 1:2 molar concentration and dissolved in 500 mL deionized water. The sample was stirred vigorously for few hours. Then, ammonia solutions were added drop-wise to the solution to initiate the precipitation of Fe-Cu binary oxides. The suspension obtained was then filtered and dried at 400°C for 24 h. The dry material was crushed and stored in a desiccator for use. The obtained material appeared in the form of fine powder. An effort was made combining iron oxide with copper oxide, to prepare this novel binary Fe-Cu adsorbent material with the aim that the prepared material would be highly efficient along with being cost effective (Zhang et al. 2013).

**Characterization of Fe-Cu binary oxide**

Fe-Cu binary oxides were characterized by powder X-ray diffraction (XRD) using Rigaku-Miniflex X-ray diffractometer with Cu-Kα radiations (λ = 0.15406 nm) in 2θ range from 20 to 80°. The morphology of the particles was observed using a scanning electron microscope. Optical properties of nanostructured Fe-Cu binary oxide samples were determined through ultraviolet (UV)-VIS spectrophotometer.

**Adsorption experiments**

All experiments were carried out under a batch condition using 100 mL Erlenmeyer flasks, each containing 50 mL of varying Cr (VI) concentrations and a certain amounts of the adsorbent. The synthetically prepared samples for batch studies were allowed to react with adsorbent at different dosages for 1 h with continuous shaking with a mechanical shaker. After the reaction, the mixture was withdrawn and transferred to centrifuge tubes and centrifuged at 8,000 rpm for 20 min. The supernatant obtained was filtered using a 0.2 μm Nalgene surfactant free cellulose acetate syringe filters. The effect of various parameters on the reduction in concentration of Cr (VI) were studied. The effect of pH in the range of 1–9 on the adsorption efficiency was studied under the following condition: contact time of 60 min on the mechanical shaker at 300 rpm stirring rate. Herein, the pH of solution was adjusted using 0.1 M HCl or/and 0.1 M NaOH. The optimal pH was then established under the condition of 0.5 g L⁻¹ adsorbent, 5 mg L⁻¹ Cr (VI) and room temperature. The effects of adsorbent dosage and initial concentration of Cr (VI) were examined in the range of 0.1–2.5 g L⁻¹ and 1–25 mg L⁻¹, respectively. All experiments were done in triplicate and the mean values were taken as the final results. The results were found to be within ±5% error.

**RESULTS AND DISCUSSION**

XRD pattern of the prepared Fe-Cu binary oxide (Fe₂O₃·CuO) is illustrated in Figure 1. The main peaks obtained at 2θ =54.8 and 2θ =58.2 shows the formation of Cu-Fe binary oxide (JCPDF No. 76-2366 and JCPDF No. 21-0290, respectively). The XRD shows that prepared binary metal oxide was rhombohedral structure as compared with the standard (JCPDF No. 21-0290). The average crystallite size was calculated from the full-width at half-maximum (FWHM) of the most intense peak of the prepared...
nanostructured Fe-Cu binary oxide using the Debye–Scherrer formula:

\[ D = \frac{k\lambda}{\beta \cos \theta} \]

where \( k = 0.9 \), \( D \) is the crystallite size (Å), \( \lambda \) (Å) is the wavelength of Cu K\( \alpha \) radiation, \( \beta \) is the FWHM (full width at half maximum) and \( \theta \) is the diffraction angle (Cullity & Stock 2001). The crystallite size of the prepared material was found to be 17.6 nm. The morphology, size, and surface of the prepared Fe-Cu binary oxide material were analysed by scanning electron microscope (SEM). Figure 2 shows that the prepared materials were agglomerates and their particle size was in the range of nanometer, resulting in the formation of a rough surface and a porous structure.

The optical absorption spectra of the sample were recorded in the range of 200–800 nm UV-VIS spectrophotometer (as shown in Figure 3). The optical absorbance spectra of nanostructured Fe-Cu binary oxide showed absorption peak at 389. The band gap of the as-prepared nanoparticles is determined from the relation (Mott & Davies 1979):

\[ (\alpha h\nu)^2 = c(h\nu - E_g) \]

where \( h\nu \) is the incident photon energy, \( c \) is the materials dependent constant, \( E_g \) is the band gap of the material, and \( \alpha \) is the absorption coefficient. The band gap of the material was calculated to be 2.2 eV which shows quantum confinement effect as the reported value of band gap for bulk alpha-Fe\(_2\)O\(_3\) was observed at 2.1 eV and for bulk CuO was observed in range of 1.2–1.45 eV (Gizhevskii et al. 2006; Al-Kuhaili et al. 2012).

**Effect of initial Cr (VI) concentration**

The effect of initial concentration of Cr (VI) on the adsorption of Cr (VI) ions in aqueous solution was examined by varying the initial Cr (VI) concentration from 1 to 25 mg L\(^{-1}\). Figure 4(a)–4(d) give the Cr (VI) removal efficiency at different initial Cr (VI) concentrations, which shows that the removal efficiency decreased with the increase in initial Cr (VI) concentration, at optimum pH = 3, contact time of 60 min and stirring rate of 300 rpm at normal room temperature 25 \( \pm \) 5 °C. The removal efficiency at adsorbent dose of 0.5 g L\(^{-1}\) was found to be 81.3%, 76.5%, 71.43%, and 73.76% for different initial Cr (VI) concentrations of 1 mg L\(^{-1}\), 5 mg L\(^{-1}\), 10 mg L\(^{-1}\), and 25 mg L\(^{-1}\), respectively. Figure 5 gives the comparative analysis of effect of initial Cr (VI) concentration vs. percent Cr (VI) removal efficiency using

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**Figure 2** | SEM images of Fe-Cu binary oxides prepared in different ratios.

**Figure 3** | (a) Ultraviolet absorption spectrum and (b) Tauc plot for Fe-Cu binary oxide nanoparticles.
Fe-Cu binary oxide nanoparticles as adsorbent at varying dosages of 0.1, 0.5, 1.0 & 2.5 g L\(^{-1}\). The decrease in the percentage removal of Cr (VI) is explained that the nanoparticles, that had limited active sites, would have become saturated above a certain concentration (Kaplan & Gilmore 2004).

**Effect of adsorbent dose on Cr (VI) removal**

The effect of adsorbent dose on the adsorption of Cr (VI) ions in aqueous solution was examined by varying the adsorbent dose from 0.1 to 2.5 g L\(^{-1}\). Figure 6(a)–6(d) give the Cr (VI) removal efficiency at different adsorbent dosages, which shows that the removal efficiency increased with the increase in adsorbent dosages, at optimum pH = 3, contact time of 60 min and stirring rate of 300 rpm at normal room temperature 25 ± 5°C. The removal efficiency at initial Cr concentration of 5 mg L\(^{-1}\) was found to be 27.9%, 76.54%, 97.48%, and 99.86% for different adsorbent dosages of 0.1, 0.5, 1.0, and 2.5 g L\(^{-1}\), respectively. Figure 7 gives the comparative analysis of effect of Fe-Cu binary oxide adsorbent dose vs. percent Cr (VI) removal efficiency at varying initial Cr (VI) concentrations of 1, 5, 10 and 25 ppm.

Increase in adsorbent dose generally increases the level of adsorption of Cr (VI) ions because of an overall increase in surface of the adsorbent (Fe-Cu binary oxide nanoparticles) which, in turn, increase the number of binding sites lead to the increase in Cr (VI) removal efficiency (Esposito et al. 2001).

**Effect of initial pH on Cr (VI) removal**

The effect of pH on removal efficiency of Cr (VI) was studied. The relation between the initial pH of the
solution and the percentage removal efficiency of Cr (VI) is shown in Figure 8. The removal efficiency of Cr (VI) decreased significantly from 76.54 to 26.82% with the increase in the initial pH from 3 to 9 at initial 5 mg L\(^{-1}\) Cr (VI) concentration and 0.5 g L\(^{-1}\) adsorbent dose. It indicated that the Fe-Cu binary oxide nanoparticles had a high reactivity at pH below 5. At low pH (enough below than pH of point of zero charge), the surface of the adsorbent will be more positively charged. Cr (VI) ions predominantly present in the form of HCrO\(_4^-\) in the acidic medium (Chowdhury et al. 2012). Thus, high removal efficiency of Cr (VI) by Fe-Cu binary oxide at
low pH indicates the strong electrostatic interaction between positively charged surface of Fe-Cu binary oxide and the negatively charged Cr (VI) ions in the liquid phase. The reaction mechanism can be written as follows (Powell et al. 1995):

\[
\begin{align*}
Fe^0 + CrO_4^{2-} + 4H_2O & \iff Cr(OH)_3 + Fe(OH)_3 + 2OH^- \\
3Fe^{2+} + CrO_4^{2-} + 8H_2O & \iff Cr(OH)_3 + 3Fe(OH)_3 + 4H^+ \\
xFe(OH)_3 + (1-x)Cr(OH)_3 & \iff (Fe_xCr_{1-x})OH_3
\end{align*}
\]

Cr (VI), by reducing from Cr (VI) to Cr (III), oxidizes Fe\(^0\) to Fe (II) or Fe (III) and Fe (II) to Fe (III) as shown in the reactions 1 and 2, respectively. Hydroxides of Fe and Cr react and precipitate to Fe (III)-Cr (III) oxy-hydroxides, and form passive oxide layers on the surface of adsorbent (see reaction 3). Insulating property of the precipitate inhibits further oxidation of Fe\(^0\)/Fe (II) and, consequently, removal rate of Cr (VI) hampered (Powell et al. 1995). Solubility of precipitate, however, strongly depends on pH. So, pH should be low enough to dissolve the precipitate and, as a result, improves the removal rate of Cr (VI) (Chang 2005). The results in this study demonstrate that the acidic conditions would accelerate the corrosion of Fe-Cu binary oxide nanoparticles and dissolution of passive layers of Fe (III)-Cr (III) oxy-hydroxides, thus enhancing removal of Cr (VI).

**Adsorption isotherm and kinetics**

All the adsorption experiments were carried out at pH = 3 (optimum pH) and room temperature. Increase in the adsorption capacity (\(q_e\)) with initial concentration of adsorbent and Cr (VI) was observed, but more time was required to reach the equilibrium point. Adsorption isotherm for the initial 0.1 g L\(^{-1}\) dose of adsorbent and 1.15 mg L\(^{-1}\) concentration of Cr (VI) is shown in the Figure 9(a). The equilibrium was achieved around 4 h in this case. Adsorption isotherm data were fitted to the Freundlich and Langmuir models. The linear forms of both the isotherm models are given below:

\[
\ln(q_e) = \ln(K_f) + \frac{1}{n} \ln(C_e) \quad \text{(Freundlich equation)}
\]

\[
\frac{C_e}{q_e} = \frac{1}{q_{max}}b + \frac{C_e}{q_{max}} \quad \text{(Langmuir equation)}
\]

**Figure 9** | Adsorption kinetics at pH 3 and room temperature: (a) adsorption isotherm for 0.1 g L\(^{-1}\) adsorbent dose, (b) Freundlich adsorption isotherm for 1 g L\(^{-1}\) adsorbent dose, (c) Langmuir adsorption isotherm for 1 g L\(^{-1}\) adsorbent dose, (d) pseudo-second-order kinetics fitting for different concentration of Cr (VI) and adsorbent dose.
where:

\( q_e \) = the adsorption capacity (i.e., the mass of adsorbate adsorbed over adsorbent at equilibrium), mg g\(^{-1}\)
\( C_e \) = the equilibrium concentration of Cr (VI) in water, mg L\(^{-1}\)
\( q_{\text{max}} \) = the maximum adsorption capacity of adsorbent, mg g\(^{-1}\)
\( K_f \) = Freundlich constant
\( n \) = Freundlich intensity parameter
\( b \) = Langmuir isotherm constant

Adsorption isotherm data for 1 g L\(^{-1}\) dose of adsorbent at different initial concentrations of Cr (VI) were fitted to Freundlich and Langmuir models as shown in Figure 9(b) and 9(c), respectively. The values of \( q_{\text{max}} \), \( K_f \), \( n \), and \( b \) were calculated from the intercepts and slopes of these plots. Calculated values are given in Table 1. Correlation coefficients \( R^2 \) show that both the models were fitted well but Freundlich isotherm model was relatively found to be the better fit in this study. This was because adsorbing sites on the surface of nanoparticles were not equal, i.e. heterogeneous surface consist, of Cu and Fe atoms. Better fitting to the Freundlich model also implied that the adsorption of Cr (VI) over the surface of Fe-Cu binary oxide was multi-layer to some extent.

A separation factor \( R_L \) (dimensionless) gives understanding of the affinity between adsorbate and adsorbent (Kundu & Gupta 2007), which can be determined using the equation:

\[
R_L = \frac{1}{1 + bC_0}
\]

If,

- \( R_L < 1.0 \) favourable adsorption
- \( R_L > 1.0 \) unfavourable adsorption
- \( R_L = 0 \) irreversible adsorption

\( C_0 \) is the initial concentration of Cr (VI) in mg L\(^{-1}\). The calculated values of \( R_L \) for different \( C_0 \) are shown in Figure 10. \( R_L \) values were between 0 and 1 which indicate the favourable adsorption of Cr on Fe-Cu binary oxide nanoparticles. Presence of a high concentration of Cr (VI) in the liquid phase results in highly favourable adsorption.

The adsorption kinetics were found to follow pseudo-second-order kinetics as shown in Figure 9(d). Assuming adsorption capacity is proportional to the number of active adsorption sites then, according to Ho & McKay (1999), the modified Lagergren equation can be written as:

\[
\frac{dq_t}{dt} = k_{\text{ads}}(q_e - q_t)^2 \quad q_t = 0 \text{ at } t' = 0
\]

where, \( q_t \) is the amount of Cr (VI) on the surface of adsorbent at time \( t' \), \( k_{\text{ads}} \) is the adsorption rate constant (g mg\(^{-1}\) h\(^{-1}\)). After integrating and rearranging, the linear form of pseudo-second-order rate expression is as follows:

\[
\frac{t}{q_t} = \frac{1}{h} + \frac{1}{q_e} t
\]

\[
h = k_{\text{ads}}q_e^2
\]

where, \( h \) is the initial adsorption rate (mg g\(^{-1}\) h\(^{-1}\)). The values of \( k_{\text{ads}} \) and \( h \) are calculated from the slope and intercept of the plots in Figure 9(d). The obtained values of \( k_{\text{ads}} \) and \( h \):

- for 0.1 g L\(^{-1}\) adsorbent: 23.82 g mg\(^{-1}\) h\(^{-1}\)
- and 1.33 mg g\(^{-1}\) h\(^{-1}\), respectively;
- for 2.5 g L\(^{-1}\) adsorbent: 14.76 g mg\(^{-1}\) h\(^{-1}\)
- and 2.2 mg g\(^{-1}\) h\(^{-1}\), respectively.

The maximum adsorption capacity of Cr (VI) calculated from Langmuir isotherm model is found to be 71.43 mg g\(^{-1}\) for the prepared Fe-Cu binary oxide nanoparticles. Maximum adsorption capacities of the various adsorbents for Cr (VI), reported in the literature, are shown in Table 2.

**Table 1** | Values of parameters of Freundlich and Langmuir adsorption isotherms for Cr (VI) adsorption (adsorbent concentration = 1 g L\(^{-1}\), pH = 3 and room temperature)

<table>
<thead>
<tr>
<th>Freundlich isotherm</th>
<th>Langmuir isotherm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_f )</td>
<td>( n )</td>
</tr>
<tr>
<td>3.59</td>
<td>0.404</td>
</tr>
</tbody>
</table>
From Table 2, it can be said that the Fe-Cu binary oxide nanoparticles prepared and used in this study has relatively more advantage over most of the adsorbents in term of adsorption capacity.

### CONCLUSION

A novel Fe-Cu binary oxide nanomaterial was prepared by a facile co-precipitation method. The crystallite size of the prepared Fe-Cu binary oxide was obtained to be 17.6 nm as calculated using Debye-Scherrer equation. The morphology of the prepared Fe-Cu binary oxide nanoparticles were found to be agglomerated, their particle size was in the range of nanometers and were found to be very effective in removing Cr (VI) from contaminated water. The absorption spectra, as well as band gap, was calculated from UV-visible spectroscopy. It was concluded that the prepared nanomaterial showed quantum confinement effect. The prepared binary metal oxide nanoparticles were used as an adsorbent for the removal of Cr (VI) from the aqueous solutions. The results illustrated that the prepared Fe-Cu binary oxide adsorbent showed a very high adsorption capacity of 71.4 mg g\(^{-1}\) at pH 3, thus performing better than the other adsorbents reported. The pH of the reaction mixture has a strong effect on the Cr (VI) removal efficiency with increasing initial pH as well as with decreasing initial Cr (VI) concentration and varying the adsorbent dose accordingly. Although maximum removal was found to be 99.99% for 25 mg L\(^{-1}\) chromium at an adsorbent dose of 2.5 g L\(^{-1}\), from the experimental results it was found that 1 g L\(^{-1}\) dosage of nanoparticles can be best suited for the removal of Cr (VI) of initial concentration up to 25 mg L\(^{-1}\). The optimum conditions for the adsorption process were obtained at acidic pH (pH = 3). Thus, the results obtained from this research provides compelling evidence that the Fe-Cu binary oxide nanoparticles may be used for in situ reductive efficacy of Cr (VI) contaminated groundwater which may lead to an innovative remediation technology proving to be cost effective and less environmentally disturbing.

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