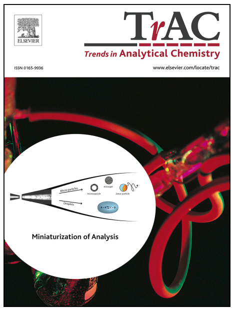

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Chromium removal from contaminated waters using nanomaterials – A review

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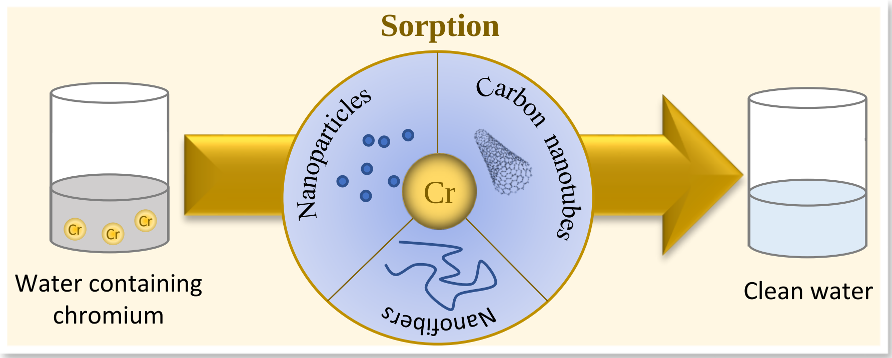
What was already made



Abstract

Current environmental policies aim to reduce the levels of toxic substances in aquatic ecosystems and to promote the water reuse after appropriate treatment of wastewater. Chromium is a hazard element present in effluents of various industries that should be reduced to achieve the objectives of those policies. Most of the results reported in the literature concern the use of nanomaterials for chromium sorption dissolved either in synthetic or mono-elemental spiked solutions. The present work reviews the results of research undertaken in the last decade on the application of various nanomaterials to decrease chromium concentrations in contaminated waters. Major factors influencing the removal efficiency were examined. Because most of the published studies are based on simple experiments with deionised water and mono contamination further studies are suggested focused on effects of natural and artificial chelators, interferences of other trace elements competing with chromium sorption, reduction the sorbent mass per water volume.

Keywords: Nanomaterials, Sorption, Chromium, Water Treatment.

1. Introduction

Present life style requires the exploitation of Earth's resources beyond their sustainability causing the reduction or depletion of limited resources [1]. Environmental issues started with the Industrial Revolution, the discharge of industrial effluents, either inadequately treated or untreated, into aquatic systems lead to the increase of hazardous inorganic and organic contaminants in rivers, lakes, estuaries and coastal areas [2]. Because of the non-degradation character of many contaminants, they are transfer to the food chains with impact on the ecosystem services and reducing the marine food safety [3,4]. Volume of dumped debris in water systems increased often surpassing the self-cleaning capacity and purification of aquatic systems. It is foreseen these discharges will increase in the future as population tends to migrate and concentrate in urban areas, as response to modern life and adversities related to climate changes.

Chromium is among the most toxic trace elements released to surface waters and ground waters due to its widespread use in industrial applications, such as leather tanning, metallurgy, electroplating and refractory [3]. The increasing number of articles published about chromium toxicity over the last 10 years [3] indicates the efforts to illustrate and remediate the chromium-bearing contamination. Trace elements can be removed from wastewaters by conventional methods, such as chemical precipitation, ion exchange, membrane filtration, coagulation/flocculation and electrochemical treatment [5]. However, these methods have low efficiency and produce large volumes of wastes. Alternatives for the treatment of water contaminated by metals are sorption methods [6]. Sorption corresponds to the transfer of the sorbate from the liquid phase to the surface of the sorbent. Sorption efficiency is influenced by various factors, such as pH, temperature, nature and amount of sorbent, initial metal concentration, ionic strength, and the presence of other contaminants [7–9]. Depending on the attractive forces between the sorbent and the sorbate, this becomes bound by physical (physiosorption) and/or chemical (chemisorption) interactions [6]. While in the physiosorption the sorbate bonds to the sorbent surface by weak forces, such as Van der Waals interactions, which is a reversible process, the chemisorption is frequently irreversible due to the presence of strong chemical bonds between the sorbent and the sorbate.

A large variety of sorbents are available to remove trace elements from waters [5], including nanomaterials with various types of coatings and chemical functionalizations [4,10]. Nanomaterials, i.e., materials and structures with at least one dimension of 1-100 nm [11], exhibit unique mechanical, optical, magnetic and chemical properties highly depended on shape, size, surface characteristics and inner structure that differ from the characteristics of particles and macroscopic surfaces of similar composition [12–14]. Sorption mechanisms by a nanomaterial sorbent are also a function of the sorbent characteristics and physical-chemical conditions of the solution where the sorbent is removed. Nanomaterials should satisfy some criteria to be used as sorbents for toxic elements removal from wastewater [15]: nontoxic; high sorption capacities; selectivity to the low concentration of contaminants; easy removal of the sorbed contaminant from the surface of the nanomaterial; recycled. Until present, a variety of nanomaterials such as carbon nanotubes, carbon based material composites, graphene, nano metal or metal oxides, and polymeric sorbents fulfil those criteria and have been studied in the removal of toxic trace elements from aqueous solutions [15].

The coupling of sorption ability and magnetic properties in certain nanomaterials have also been explored envisaging a new class of nanosorbents [16,17]. Magnetic nanosorbents offer the great advantage of allowing fast recovery by employing magnetic separation technologies. A number of nanosorbents comprising magnetite nanoparticles have been reported by our laboratories, which include core/shell nanoparticles for the removal of heavy metal ions [18] and magnetic bionanocomposites for the removal of organic pollutants [19]. The successful implementation of magnetic nanosorbents depends, among other factors, on their efficiency for the selective uptake of pollutants, which requires further developments concerning the type of surface chemistry involved. The intensive use of nanomaterials may have some environmental risks and impacts on human health [13]. It is hence crucial to evaluation the nanoparticles toxicity, which depends on their aggregation, agglomeration, dispensability, size, solubility, surface area, surface charge and surface chemistry [20].

The objective of this review is to serve as a one-stop-reference by bringing together results of the most recent research on the application of synthetic nanomaterials in the treatment of chromium-contaminated waters.

2. Chromium

2.1. Chemistry

Chromium (atomic number 24) is a steely-grey, lustrous, hard and brittle metal occurring in the earth's crust crystalline solid [21] with atomic weight 51.996 u, melting point 1907 ºC and boiling point 2672 ºC. Among the various oxidation states, the most common in the aquatic environment are the trivalent(III) and hexavalent(VI) states, which differ in physicochemical properties and toxicity. Whereas Cr(III) is an essential nutrient in trace amounts, Cr(VI) is toxic and carcinogenic. Solubility of the compounds varies: Cr(III) compounds, such as $Cr(OH)_3$ which precipitate at neutral pH (**Figure 1**), are generally insoluble in water; Cr(VI) is highly soluble in the full pH range [3]. The ratio between chromium hexavalent, Cr(VI), and trivalent, Cr(III), strongly depends on the solution pH, oxidative properties (redox potential) and kinetics. Depending on these conditions, chromium in water can hence change from one oxidation state to another [21]. As presented in **Figure 1,** there are two predominant forms of Cr(VI) depending on the solution pH: $HCrO_4^-$ is predominant at pH between 2.0 and 6.5, while CrO_4^{2-} is predominant at pH>6.5. Cr(III) in aqueous solution exists in four main forms, in which soluble Cr^{3+} complexes predominate at pH <4.0, and Cr(III) precipitates as $Cr(OH)_3$ at pH between 5.5 and 12.5.

Chromium speciation in aquatic systems may be modified by external factors such as solar radiation, complexation in water, redox gradient between bottom water and the upper sediment layer, and interact with other redox sensitive elements such as iron and manganese [22]. **Figure 2** illustrates the transformations and pathway of chromium species in the water column, including the interfaces water-atmosphere and water-sediment [23]. Direct assessment of Cr speciation in natural waters is difficult because determination of the Cr forms present in solution implies the preservation of species integrity during the sample storage, pre-treatment, extraction and the determination procedure. Reliability of the results requires the use of adequate analytical methodologies and speciation analysis.

2.2. Toxicity

Chromium speciation influences uptake by the organisms and toxicity [24]. Chromium residues tend to be amplified along the food chain [25,26]. Although Cr(VI) is considered one hundred times more toxic than Cr(III) [27], overall chromium and its compounds have been classified to be human carcinogens by the Institute for the Regulation of Water and Solid Waste (IARC). Chromium causes irritation and ulcers in the stomach and small intestine, damage on kidney and liver, sperm, and male reproductive system [21]. Also, it can cause respiratory problems, including irritation of the lining of the nose, runny nose, and breathing problems such as asthma, cough, shortness of breath and wheezing. Chromium can lead to cancer in lung, stomach and intestinal tract. **Table 1** gives the concentration limits of chromium for different uses of water, according to criteria of international organizations such as the Agency for Toxic Substances & Disease Registry (ATSDR) and World Health Organization (WHO). Regarding Cr threshold for drinking water, although most EU countries apply a legal limit of 50 µg/L of chromium, limits are going to be reduced soon to 25 µg/L, according to a recent recast of the Directive 2001/83/EC, which occurred in 2018. A few years ago, in some Italian cities, chromium levels were already at the limits of the Directive 2001/83/EC on the quality of water intended for human consumption. This has led Italy to notify the European Commission of the need to change the parameters of hexavalent chromium in drinking water, as well as to introduce a limit of 10 µg/L for Cr(VI) in drinking water in the current Legislative Decree. Also, Italy announces that detection of chromium concentrations above the legal limit will imply investigations on water source (spring, groundwater, …). Besides Italy, there are other EU countries, such as Greece, concerned about high levels of hexavalent chromium in waters, which frequently exceed the permissible limit for human consumption [28].

2.3. Natural sources and industrial emissions of chromium

Both, natural processes and anthropogenic emissions contribute to the presence of chromium in aquatic systems. , Weathering of rocks and soil erosion and leaching by rainwater are major natural processes favouring the input of chromium to rivers, lakes, estuaries, and ocean [29]. Discharges of industries such as electroplating, leather tanning, stainless steel welding, and ferrochrome and chrome pigment production contribute to chromium concentrations in aquatic environment above the regional baseline values [21,30]. Chromium (hexavalent chromium) has a key role in metal finishing industry modifying the surface of a product to enhance its appearance and reflectivity, such as colour or brightness, wear resistance, corrosion resistance, electrical resistance, chemical resistance, hardness, or to produce surface characteristics essential for subsequent operations [31]. These processes are applied in telecommunications, aviation, construction, jewellery, transport, among other sectors. More than 650 galvanizing plants were installed in European countries affiliated to the European General Galvanizers Association (Woolley, 2008) being distributed mainly by Germany (160), Italy (90), Spain (72), United Kingdom (62) and France (60). The release of trivalent chromium worldwide responsible for approximately 20% of chromium emissions is the leather tanning industry where putrescible hide or skin is converted into leather. The permanent stabilization of the skin matrix against biodegradation is possible using basic chromium sulphate [32]. Although this industry is not critical in Europe, it has a high impact in Asia, Africa, and South America (Public Partnership for Better Innovation Policies and Instruments in Support of Eco-Innovation: ECOPOL, 2013). For example, leather tannery industry in China is responsible for 20% of chromium discharges into water, the average total amount between 1990 and 2009 reaching more than 0.5 thousand tons per year [34].

The European Pollutant Release and Transfer Register (E-PRTR) estimates the quantities of 91 contaminants released to air, water and land. Considering the period 2007-2015 this document reports the annual release of 550 tons of Cr to the European waters. **Figure 3** compares the contribution of various industrial activities on the emission of chromium in 2014 and 2015. The sector “Production and processing of metals” accounts for more than 60% of the chromium emission into the water.

3. Material and Methodology

Numerous studies have been published on chromium sorption in aqueous phase using various materials and in particular synthetic nanomaterials [9,35–39]. To select the articles published in the literature with respect to chromium sorption by synthetic nanomaterials search was done in the principal collection of Web of Science. The following keywords were used: (i) chromium; (ii) nanomaterial or nanoparticle or nanosorbent; (iii) uptake or sorption; (iv) removal or remediation or water. The search was confined to the period 2007-2017. Approximately 200 articles were identified, although a few of them were focused on the development of quantification methodologies, being less relevant on chromium sorption by synthetic nanomaterials.

For each selected article, it was extracted the information related to the parameters considered relevant in sorption [7–9]: name and nature of the sorbent, mass of the sorbent with respect to the water volume, type of water used in the experiment, type of experiment (single or other contaminants besides chromium), pH, temperature, contact time between the sorbent and the solution, initial concentration of chromium, chromium species initially present in solution, and removal efficiency.

4. Results and Discussion

Table 2 lists the synthetic nanomaterials and the experimental conditions employed in the studies of the selected articles from the literature. In order to encompass the collected information in a single Table, intervals of values are presented for the uptake capacity or removal efficiency of each nanomaterial or group of nanomaterials, as well as for the relevant parameters aforementioned.

Type of materials. Among the various materials used for chromium removal, nanoparticles have been the most common, either using just the core nanoparticles [9,40–46], nanoparticles with functionalization [35,47–49], or modified nanoparticles incorporated on substrates [36,50]. Other type of materials have been used, such as nanocomposites [37,51,52], nanofibers [38] and carbon nanotubes [39]. In present review, nanomaterials like zero-valent iorn nanoparticels (nZVI) were not found. In the first step towards the use of this material the toxic Cr(VI) is reduced to the less hazardous Cr(III), which is then removed by sorption to the nZVI surface and precipitation by iron-hydroxides [53,54].

Interactions with other elements. Most of the studies mentioned in **Table 2** describe the chromium sorption experiments using mono-elemental systems, Cr being the only contaminant to be treated. Only a few studies tested both mono-elemental and multi-elemental systems. Distilled or milli-Q water have been considered. Absence of competitive ions or other contaminants are simplistic approaches to the complex conditions existing in aquatic systems or contaminated waters. The lack of chromium sorption experiments using multi-elemental systems, where Cr was not the only contaminant to be treated, is a weakness in this kind of research.

Type of solutions. Only a few studies addressed the treatment of contaminated waters as real samples, such as groundwater, effluents or wastewater [41,46,48,55,56]. Chen et al. [57] have simulated natural waters by testing solutions of different complexity, deionized distilled water, tap water, mountain stream water and river water. Although the absence of competitive ions or other contaminants be the most common approach in this kind of research, the study of nanomaterials behaviour in natural waters is crucial before the material be implemented in the market. Real waters have varied and complex composition; thus, some researchers try to simulate the reality through the dissolution of salts that put in the waters the ions found in natural systems.

Temperature. Most of the removal experiments have been tested at temperature between 20 and 25ºC, presumably to be more practical and reduce associated costs with cooling and heating. Other studies were performed approximately at 30ºC [39,48,49,51,58–63], at 35ºC [37], and even at 40ºC [64,65] most likely ajusting to the natural conditions existing in warmer countries. Apart from the cases described by [8,9,39,66,67], efficiency of chromium sorption increases with temperature.

Contact time. In general, contact time between the nanomaterial and the contaminant were less than 2 days, although data exist for 3 days [55], 7 days [68] and 15 days [56]. Removal experiments for industrial application should be performed during a contact period between the nanomaterial and the contaminant less than 48 hours to be feasible for the industry. This is because very long sorption processes imply the existence of industrial tanks that are inactive for a long time. On the other hand, treated effluents must be discharged quickly without endangering the life of aquatic organisms that are exposed to these effluents.

pH. Removal of Cr(VI) was tested at pH from 2 to 3 [9,39,42–44,66,69], although some authors have been studied the removal at more realist pH interval, 5-8 [40,70], which is the pH found in actual industrial effluent. Values of optimal pH in the removal of Cr(III) were between 5 and 7 [9,38,42,48,51,71].

Amount of sorbent. It is well documented that, for the same Cr concentration, the rate of sorption increases with the amount of sorbent. However, the larger amount of material used should be avoided because it will generate greater amounts of residues to be treated increasing the cost of process. Several works have tested low doses of sorbent per volume of solution, such as Bisht et al. [72], Paul et al. [58], Kaprara et al. [40], Debnath et al. [45], Tahergorabi et al. [47], Khan et al. [43], Simeonidis et al. [70], Guo et al. [73], Mao et al. [60], Moradi and Baniamerian [74], Srivastava et al. [37], Mohamed et al. [67] and Babaei et al. [36]. In particular Bisht et al. [72] used 5, 10, 15, 20, 25 and 30 mg/L of EDTA-Fe_3O_4 nanoparticles, Paul et al. [58] used 10 mg/L and 50 mg/L of TiO_2 nanoparticles and Kaprara et al. [40] used 25 mg/L of Sn(II) oxy-hydroxides nanoparticles for Cr(VI) removal.

Chromium concentrations. For the removal experiments, a wide range of chromium concentrations has been reported in the literature, between 10 µg/L [40] and 11 000 000 µg/L [75]. The maximum allowed concentration of total chromium in residual waters is 2 000 µg/L, meaning the studies that used higher concentrations are unrealistic. In this way, some studies [9,40,78,43,50,52,68–70,76,77] run their experiments with lower concentrations, taking into consideration the allowed limits of chromium in water. Among these, Chowdhury and Yanful [76], Simeonidis et al. [70] and Gifford et al. [68] were the only ones that studied concentration equal or <2000 µg/L and Kaprara et al. [40] studied the removal of 10 µg/L of chromium using Sn(II) oxy-hydroxides nanoparticles.

Chromium speciation. Cr(VI) have been the most investigated species, although some researchers have run experiments with Cr(III) forms [38,47,48,51,71]. Others studies used with both Cr(III) and Cr(VI) [9,42,69,77,78]. Only a few studies mention the analytical methodologies to discriminate the quantification of Cr(III) and Cr(VI) during the removal process. Most of the methodologies referred in the works of **Table 2** are only able to measure total Cr and so most of the values reported for uptake capacity or removal efficiency are based on the initial and final concentrations regardless the starting chromium species. Using the materials mentioned in **Table 2** both Cr species are removed through sorption mechanisms. However, the mechanisms of removal crucially depend on Cr speciation. According to Debnath et al. [45], Cr(VI) ions sorb to $CaFe_2O_4$ NPs through electrostatic interactions. Rajabathar et al. [79] suggest that the sorption mechanism of Cr(VI) is purely an electrostatic interaction. Luther et al. [69], Cantu et al. [77], Bisht et al. [72], Srivastava et al. [37], Valle et al. [9] and Mahmoud et al. [42] propose that mechanisms for the binding of chromium(VI) is mainly physisorption. Despite those studies suggesting physical interaction between Cr(VI) and sorbents, not all authors agree on the nature of the interaction during the sorption process. The presence of chemical bonds is suggested as a secondary mechanism [69], although Babaei et al. [36] suggest that sorption is governed by chemical forces rather than physical electrostatic interactions. Even so, the removal of Cr(VI) is undoubtedly a sorption process. Regarding the reaction of Cr(III) with the different materials, the binding is through an ion or molecular exchange mechanism combined with some kind of physisorption [69,77]. Egodawatte et al [38] proposed that the binding mechanism between the nanofibers and Cr(III) involves the sorption of a positive complex on the surface of the materials. Arthy et al. [51] suggested a chemisorption mechanism. When no sorption mechanism is proposed in the articles, the interaction between Cr(III) and the materials is described as sorption process [48,71].

Best material performance. Lastly, magnetic iron oxide nanoparticles/sugarcane bagasse composite [51] and Cr(VI)-imprinted poly(HEMAH) nanoparticles [75] were the materials reported in the literature in the last years as being the ones with the most affinity for Cr(III) and Cr(VI) uptake, achieving a capacity of approximately 518 mg/g and 3 830 mg/g, respectively. However, maximum uptake capacity is a tricky parameter for the evaluation of a material efficiency. This parameter depends on the experimental conditions used, namely initial metal concentration and amount of nanomaterial used. Thus, the sorption performance of a material can not be assessed by considering only the sorption capacity value achieved.

Application of synthetic nanomaterials in real industrial effluents. The use of nanomaterials at technological level is still a big question to be solved. The materials presented in **Table 2** are far from being implemented in the market, with a maximum Technology Readiness Level (TRL) for industrial and socioeconomical aspect of 3.

Then, the published works are just a probe of concept, showing that there was a poor attempt to apply the nanomaterials to real samples and describing mainly its application in synthetic or mono-elemental spiked solutions. In this context, further laboratory removal essays are still required, never forgetting that these conditions must be realistic and adapted to the application. And after all laboratory tests are optimized using realistic experimental conditions, it is necessary to test the material in real effluents because the behaviour of a material may be very good in a synthetic contaminated water, but the same could not occur in the real system. For example, different industrial effluents have different composition and it is not possible to mimic all the real scenarios.

There are no reported successful case of applications to real effluents since the few studies that evaluated the potential of nanomaterials in real industrial effluents, either adding chromium to the samples of water or using a high amount of sorbent (economically unviable) and even performing the sorption experiments in very low volumes of water. However, some important considerations to apply a nanomaterial in real industrial effluents are the following:

- The treatment systems usually used are in batch.
- The effluents can need some kind of pre-treatment.
- Nanomaterials can be on-single use or a mixture of nanomaterials can be used. In the last case, it is necessary to address in which way the recovery process will be carried out; the ideal situation is the recovery of chromium in a way it can be further reused without any treatment – circular economy.

- The application of nanomaterials in industrial streams with large contents of particulate matter or high chemical oxygen demand (COD) content may not be successful.

Toxicity of remediated water. Along with the development of new removal processes to remediate water, dedicated research regarding environmental risks is still lacking. Up to now several studies have described technical properties and applications of nanomaterials for Cr removal from water (**Table 2**), but scarce information is available concerning their impacts towards aquatic organisms, in particular, no information is available on the potential toxicity of the Cr remediated water. It is important to test the ecotoxicity of treated water since recent works (not yet published) have shown that remediated waters can remain toxic for the aquatic organisms. It is also needed to access the environmental risk of the nanomaterials itself because of non-stability of some nanomaterials such as silver and gold nanoparticles, which can have impact on aquatic ecosystems due to toxicity of remaining material.

5. Conclusions and Perspectives

This review summarizes the information published in the literature between 2007 and 2017 on the influence of various factors on sorption of chromium by nanomaterials. Although some studies dealt with Cr (VI) or Cr(III), changes of oxidation status were not tested during the sorption process since the analytical methodology used is for determination of total chromium. Articles evidence the high adsorption capacity of nanomaterials for chromium species, though most studies have been focused on mono-Cr spiked solution of Milli-Q water. Despite the effectiveness in decreasing chromium concentrations at simple laboratory experiments, the viability and success of nanomaterials as sorbents depends on crucial factors that need further evaluation. The effect of natural and artificial chelators, commonly present in contaminated waters is a key step to approach realistic conditions. The effect of interferences of other trace elements competing with chromium sorption should be studied. In order to minimize wastes that ultimately might result in the discharge of nanoparticles to the environment, a reduction of the mass of sorbent per water volume is envisaged. Furthermore, it is important to consider in future studies the potential toxic impacts derived from Cr remediated water. As additional concluding remarks, in order to identify the best conditions to test the efficacy of nanosorbents it is crucial to carried out a first set of experiments varying the amount of sorbent used, the solution pH, the chromium concentration and to monitor the concentration of chromium in solution with time. With these experiments it would be possible to evaluate the influence of the different experimental parameters on the sorption process. Moreover, to optimize the performance of a specific nanomaterial in a determined matrix and expedite the study of the sorption process, a statistical tool designated by response surface methodology (RSM) can be applied. This tool has already been used in previous studies to remove contaminants, including chromium [80], using nanomaterials. Also, RSM allows not only to study the impact of the experimental parameters on the desired response (in this case, removal of chromium), but also to determine the best conditions to obtain the best performance of the material. This review allowed identifying the main limitations of chromium sorption process using synthetic nanomaterials, based on the works published until the date.

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References

[1] J. Kitzes, M. Wackernagel, J. Loh, A. Peller, S. Goldfinger, D. Cheng, K. Tea, Shrink and share: humanity's present and future Ecological Footprint., Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363 (2008) 467–475.

[2] P.F.M. Verdonschot, B.M. Spears, C.K. Feld, S. Brucet, H. Keizer-Vlek, A. Borja, M. Elliott, M. Kernan, R.K. Johnson, A comparative review of recovery processes in rivers, lakes, estuarine and coastal waters, Hydrobiologia. 704 (2013) 453–474.

[3] W. Jin, H. Du, S. Zheng, Y. Zhang, Electrochemical processes for the environmental remediation of toxic Cr(VI): A review, Electrochim. Acta. 191 (2016) 1044–1055.

[4] V.N. Thekkudan, V.K. Vaidyanathan, S.K. Ponnusamy, C. Charles, S. Sundar, D. Vishnu, S. Anbalagan, V.K. Vaithyanathan, S. Subramanian, Review on nanoadsorbents: a solution for heavy metal removal from wastewater, IET Nanobiotechnology. 11 (2016) 213–224.

[5] F. Fu, Q. Wang, Removal of heavy metal ions from wastewaters: A review, J. Environ. Manage. 92 (2011) 407–418.

[6] T.A. Kurniawan, G.Y.S. Chan, W.-H. Lo, S. Babel, Physico-chemical treatment techniques for wastewater laden with heavy metals, Chem. Eng. J. 118 (2006) 83–98.

[7] S. Babel, T.A. Kurniawan, Low-cost adsorbents for heavy metals uptake from contaminated water: a review., J. Hazard. Mater. 97 (2003) 219–43.

[8] S. Dubey, S.N. Upadhyay, Y.C. Sharma, Optimization of removal of Cr by γ-alumina nano-adsorbent using response surface methodology, Ecol. Eng. 97 (2016) 272–283.

[9] J.P. Valle, B. Gonzalez, J. Schulz, D. Salinas, U. Romero, D.F. Gonzalez, C. Valdes, J.M. Cantu, T.M. Eubanks, J.G. Parsons, Sorption of Cr(III) and Cr(VI) to K2Mn4O9 nanomaterial a study of the effect of pH, time, temperature and

interferences, Microchem. J. 133 (2017) 614–621.

[10] M. Hua, S. Zhang, B. Pan, W. Zhang, L. Lv, Q. Zhang, Heavy metal removal from water/wastewater by nanosized metal oxides: A review, J. Hazard. Mater. 211–212 (2012) 317–331.

[11] E. Francisquini, J. Schoenmaker, J.A. Souza, Nanopartículas Magnéticas e suas Aplicações, in: Química Supramol. e Nanotecnologia, 1st ed., 2014: pp. 269–288.

[12] M.A. Martins, T. Trindade, Os nanomateriais e a descoberta de novos mundos na bancada do químico, Quim. Nova. 35 (2012) 1434–1446.

[13] F.H. Quina, Nanotecnologia e o Meio Ambiente: Perspectivas e Riscos, Quim. Nov. 27 (2004) 1028–1029.

[14] T. Trindade, P.J. Thomas, Defining and using very small crystals, in: J. Reedijk, K. Poeppelmeier (Eds.), Compr. Inorg. Chem. II, Vol.4, Oxford: Elsevier, 2013: pp. 343–369.

[15] X. Wang, Y. Guo, L. Yang, M. Han, J. Zhao, X. Cheng, Nanomaterials as Sorbents to Remove Heavy Metal Ions in Wastewater Treatment, J. Environ. Anal. Toxicol. 2 (2012) 154–158.

[16] H. Zhang, R.G. Mcdowell, L.R. Martin, Y. Qiang, Selective extraction of heavy and light lanthanides from aqueous solution by advanced magnetic nanosorbents, ACS Appl. Mater. Interfaces. 8 (2016) 9523–9531.

[17] Z. Mokadem, S. Saïdi-Besbes, G. Agusti, A. Elaissari, A. Derdour, Magnetic nanoadsorbents for metal remediation, J. Colloid Sci. Biotechnol. 5 (2016) 11–133.

[18] D.S. Tavares, A.L. Daniel-Da-Silva, C.B. Lopes, N.J.O. Silva, V.S. Amaral, J. Rocha, E. Pereira, T. Trindade, Efficient sorbents based on magnetite coated with siliceous hybrid shells for removal of mercury ions, J. Mater. Chem. A. 1 (2013) 8134–8143.

[19] T. Fernandes, S. Soares, T. Trindade, A. Daniel-da-Silva, Magnetic Hybrid Nanosorbents for the Uptake of Paraquat from Water, Nanomaterials. 7 (2017) 68.

[20] H.A. Khan, R. Shanker, Toxicity of Nanomaterials, Biomed Res. Int. 2015 (2015) 2.

[21] ATSDR, Toxicological Profile for Chromium, Agency Toxic Subst. Dis. Regist. (2012).

[22] J. Gorny, G. Billon, C. Noiriel, D. Dumoulin, L. Lesven, B. Madé, Chromium behavior in aquatic environments: A review, Environ. Rev. 24 (2016) 503–516.

[23] B. Markiewicz, I. Komorowicz, A. Sajnóg, M. Belter, D. Barałkiewicz, Chromium

and its speciation in water samples by HPLC/ICP-MS - technique establishing metrological traceability: A review since 2000, Talanta. 132 (2015) 814–828.

[24] J. Ščančar, R. Milačič, A critical overview of Cr speciation analysis based on high performance liquid chromatography and spectrometric techniques, J. Anal. At. Spectrom. 29 (2014) 427–443.

[25] C.T. Driscoll, R.P. Mason, H.M. Chan, D.J. Jacob, N. Pirrone, Mercury as a global pollutant: Sources, pathways, and effects, Environ. Sci. Technol. 47 (2013) 4967–4983.

[26] A. Renzoni, F. Zino, E. Franchi, Mercury Levels along the Food Chain and Risk for Exposed Populations, Environ. Res. 77 (1998) 68–72.

[27] W. Zhou, B.-C. Yin, B.-C. Ye, Highly sensitive surface-enhanced Raman scattering detection of hexavalent chromium based on hollow sea urchin-like TiO2@Ag nanoparticle substrate, Biosens. Bioelectron. 87 (2017) 187–194.

[28] E. Tziritis, E. Kelepertzis, G. Korres, D. Perivolaris, S. Repani, Hexavalent chromium contamination in groundwaters of Thiva Basin, Central Greece, Bull. Environ. Contam. Toxicol. 89 (2012) 1073–1077.

[29] P.Z. Ray, H.J. Shipley, Inorganic nano-adsorbents for the removal of heavy metals and arsenic: a review, RSC Adv. 5 (2015) 29885–29907.

[30] Y. Gong, J. Tang, D. Zhao, Application of iron sulfide particles for groundwater and soil remediation: A review, Water Res. 89 (2016) 309–320.

[31] G.M. Naja, B. Volesky, Toxicity and Sources of Pb, Cd, Hg, Cr, As, and Radionuclides in the Environment, in: Heavy Met. Environ., 1st ed., 2009: pp. 13–62.

[32] A.A. Belay, Impacts of Chromium from Tannery Effluent and Evaluation of Alternative Treatment Options, J. Environ. Prot. (Irvine,. Calif). 1 (2010) 53–58.

[33] Public Partnership for Better Inovation Policies and Instruments in Support of Eco-Innovation: ECOPOL, Leather - Tanning with Chromium, (2013). https://ecopolproject.blogspot.de/2013/10/leather-tanning-with-chromium.html (accessed February 1, 2018).

[34] H. Cheng, T. Zhou, Q. Li, L. Lu, C. Lin, Anthropogenic chromium emissions in China from 1990 to 2009, PLoS One. 9 (2014) 87753–87761.

[35] B. Huang, C. Qi, Z. Yang, Q. Guo, W. Chen, G. Zeng, Pd/Fe3O4 nanocatalysts for highly effective and simultaneous removal of humic acids and Cr(VI) by electro-Fenton with H2O2 in situ electro-generated on the catalyst surface, J. Catal. 352 (2017) 337–350.

[36] A.A. Babaei, M. Ahmadi, G. Goudarzi, N. Jaafarzadeh, Z. Baboli, Adsorption of chromium(VI) from saline wastewater using spent tea-supported magnetite nanoparticle, Desalin. Water Treat. 57 (2015) 12244–12256.

[37] S. Srivastava, S.B. Agrawal, M.K. Mondal, Synthesis, characterization and application of Lagerstroemia speciosa embedded magnetic nanoparticle for Cr(VI) adsorption from aqueous solution, J. Environ. Sci. 55 (2017) 283–293.

[38] S. Egodawatte, K.E. Greenstein, I. Vance, E. Rivera, N. V Myung, G.F. Parkin, M. Cwiertny, S.C. Larsen, Electrospun hematite nanofiber/mesoporous silica core/shell nanomaterials as an efficient adsorbent for heavy metals, RSC Adv. 6 (2016) 90516–90525.

[39] C. Lee, S. Kim, Cr(VI) Adsorption to Magnetic Iron Oxide Nanoparticle-Multi-Walled Carbon Nanotube Adsorbents, Water Environ. Res. 88 (2016) 2111–2120.

[40] E. Kaprara, N. Tziarou, K. Kalaitzidou, K. Simeonidis, L. Balcells, The use of Sn(II) oxy-hydroxides for the effective removal of Cr(VI) from water: Optimization of synthesis parameters, Sci. Total Environ. 605–606 (2017) 190–198.

[41] V. Srivastava, T. Kohout, M. Sillanpää, Potential of cobalt ferrite nanoparticles (CoFe2O4) for remediation of hexavalent chromium from synthetic and printing press wastewater, J. Environ. Chem. Eng. 4 (2016) 2922–2932.

[42] M.E. Mahmoud, A.E.H. Abdou, M.E. Sobhy, Engineered nano-zirconium oxide-crosslinked-nanolayer of carboxymethyl cellulose for speciation and adsorptive removal of Cr(III) and Cr(VI), Powder Technol. 321 (2017) 444–453.

[43] S.U. Khan, R. Zaidi, S.Z.. Hassan, I.. H.. Farooqi, A. Azam, Application of Fe-Cu binary oxide nanoparticles for the removal of hexavalent chromium from aqueous solution, Water Sci. Technol. 74 (2016) 165–175.

[44] S. Rajput, C.U. Pittman, D. Mohan, Magnetic magnetite (Fe3O4) nanoparticle synthesis and applications for lead (Pb2+) and chromium (Cr6+) removal from water, J. Colloid Interface Sci. 468 (2016) 334–346.

[45] A. Debnath, M. Majumder, M. Pal, N.S. Das, K.K. Chattopadhyay, B. Saha, A. Debnath, M. Majumder, M. Pal, Enhanced Adsorption of Hexavalent Chromium onto Magnetic Calcium Ferrite Nanoparticles: Kinetic, Isotherm, and Neural Network Modeling, J. Dispers. Sci. Technol. 37 (2016) 1806–1818.

[46] N. Sezgin, A. Yalçın, Y. Köseoğlu, MnFe2O4 nano spinels as potential sorbent for adsorption of chromium from industrial wastewater, Desalin. Water Treat. 57 (2016) 16495–16506.

[47] M. Tahergorabi, A. Esrafili, M. Kermani, M. Shirzad-Siboni, Application of thiol-functionalized mesoporous silica-coated magnetite nanoparticles for the adsorption of heavy metals, Desalin. Water Treat. 57 (2016) 19834–19845.

[48] X. Guan, J. Chang, H. Fan, A magnetically-separable Fe3O4 surface grafted with polyacrylic acid for chromium(III) removal from tannery effluents, RSC Adv. 5 (2015) 50126–50136.

[49] G. Lan, X. Hong, Q. Fan, B. Luo, P. Shi, X. Chen, Removal of Hexavalent Chromium in Wastewater by Polyacrylamide Modified Iron Oxide Nanoparticle, J. Appl. Polym. Sci. 131 (2014) 40945–40955.

[50] M. Biswal, K. Bhardwaj, P.K. Singh, P. Singh, P. Yadav, A. Prabhune, C. Rode, S. Ogale, Nanoparticle-loaded multifunctional natural seed gel-bits for efficient water purification, RSC Adv. 3 (2013) 2288–2295.

[51] M. Arthy, B.R. Phanikumar, Efficacy of Iron-Based Nanoparticles and Nanobiocomposites in Removal of Cr3+, J. Hazardous, Toxic, Radioact. Waste. 20 (2016) 28.

[52] W. Chooaksorn, R. Nitisoravut, C. Polprasert, S. Babel, K. Laohhasurayotin, W. Kangwansupamonkon, Enhancement of Cr(VI) Ion Removal Using Nanochitosan Coated on Bituminous Activated Carbon, Water Environ. Res. 88 (2016) 2150–2158.

[53] J. Němeček, O. Lhotský, T. Cajthaml, Nanoscale zero-valent iron application for in situ reduction of hexavalent chromium and its effects on indigenous microorganism populations, Sci. Total Environ. 485–486 (2014) 739–747.

[54] M. Taghizadeh, D.Y. Kebria, G. Darvishi, F.G. Kootenaei, The Use of Nano Zero Valent Iron in Remediation of Contaminated Soil and Groundwater, Int. J. Sci. Res. Environ. Sci. 1 (2013) 152–157.

[55] M. Kumari, C.U.P. Jr., D. Mohan, Heavy metals [chromium (VI) and lead (II)] removal from water using mesoporous magnetite (Fe3O4) nanospheres, J. Colloid Interface Sci. 442 (2015) 120–132.

[56] M.P. Watts, V.S. Coker, S.A. Parry, R.A.D. Pattrick, R.A.P. Thomas, R. Kalin, J.R. Lloyd, Biogenic nano-magnetite and nano-zero valent iron treatment of alkaline Cr(VI) leachate and chromite ore processing residue, Appl. Geochemistry. 54 (2015) 27–42.

[57] X. Chen, K.F. Lam, K.L. Yeung, Selective removal of chromium from different aqueous systems using magnetic MCM-41 nanosorbents, Chem. Eng. J. 172 (2011) 728–734.

[58] M.L. Paul, J. Samuel, R. Roy, N. Chandrasekaran, Studies on Cr(VI) removal from aqueous solutions by nanotitania under visible light and dark conditions, Bull. Mater. Sci. 38 (2015) 393–400.

[59] M.A. Behnajady, S. Bimeghdar, Synthesis of mesoporous NiO nanoparticles and their application in the adsorption of Cr(VI), Chem. Eng. J. 239 (2014) 105–113.

[60] N. Mao, L. Yang, G. Zhao, X. Li, Y. Li, Adsorption performance and mechanism of Cr(VI) using magnetic PS-EDTA resin from micro-polluted waters, Chem. Eng. J. 200–202 (2012) 480–490.

[61] E. Akoz, S. Erdemir, M. Yilmaz, Immobilization of novel the semicarbazone derivatives of calix[40]arene onto magnetite nanoparticles for removal of Cr(VI) ion, J. Incl. Phenom. Macrocycl. Chem. 73 (2012) 449–458.

[62] J. Saikia, B. Saha, G. Das, Efficient removal of chromate and arsenate from individual and mixed system by malachite nanoparticles, J. Hazard. Mater. 186 (2011) 575–582.

[63] S. Debnath, K. Biswas, U.C. Ghosh, Removal of Ni(II) and Cr(VI) with Titanium(IV) Oxide Nanoparticle Agglomerates in Fixed-Bed Columns, Ind. Eng. Chem. Res. 49 (2010) 2031–2039.

[64] M. Ataabadi, M. Hoodaji, A. Tahmourespour, M. Kalbasi, M. Abdouss, Optimization of factors affecting hexavalent chromium removal from simulated electroplating wastewater by synthesized magnetite nanoparticles, Environ. Monit. Assess. 187 (2015) 4165–4175.

[65] S. Mohan, Y. Singh, D.K. Verma, S.H. Hasan, Synthesis of CuO nanoparticles through green route using Citrus limon juice and its application as nanosorbent for Cr(VI) remediation : Process optimization with RSM and ANN-GA based model, Process Saf. Environ. Prot. 96 (2015) 156–166.

[66] Y. Pang, G. Zeng, L. Tang, Y. Zhang, Y. Liu, X. Lei, Preparation and application of stability enhanced magnetic nanoparticles for rapid removal of Cr(VI), Chem. Eng. J. 175 (2011) 222–227.

[67] A. Mohamed, W.S. Nasser, T.A. Osman, M.S. Toprak, M. Muhammed, A. Uheida, Removal of chromium (VI) from aqueous solutions using surface modified composite nanofibers, J. Colloid Interface Sci. 505 (2017) 682–691.

[68] M. Gifford, M. Chester, K. Hristovski, P. Westerhoff, Reducing environmental impacts ofmetal (hydr)oxide nanoparticle embedded anion exchange resins using anticipatory life cycle assessment, Environ. Sci. Nano. 3 (2016) 1351–1360.

[69] S. Luther, N. Brogfeld, J. Kim, J.G. Parsons, Study of the thermodynamics of chromium(III) and chromium(VI) binding to iron (II/III) oxide or magnetite or ferrite and magnanese(II) iron (III) oxide or jacobsite or manganese ferrite nanoparticles, J. Colloid Interface Sci. 400 (2013) 97–103.

[70] K. Simeonidis, E. Kaprara, T. Samaras, M. Angelakeris, N. Pliatsikas, G. Vourlias, Optimizing magnetic nanoparticles for drinking water technology : The case of Cr(VI), Sci. Total Environ. 535 (2015) 61–68.

[71] T. Shahriari, G.N. Bidhendi, N. Mehrdadi, A. Torabian, Effective parameters for the

adsorption of chromium(III) onto iron oxide magnetic nanoparticle, Int. J. Environ. Sci. Technol. 11 (2014) 349–356.

[72] G. Bisht, S. Neupane, R. Makaju, Supercritical CO2 Assisted Synthesis of EDTA-Fe3O4 Nanocomposite with High Adsorption Capacity for Hexavalent Chromium, J. Nanomater. 2016 (2016) 10.

[73] J. Guo, X. Cai, Y. Li, R. Zhai, S. Zhou, P. Na, The preparation and characterization of a three-dimensional titanium dioxide nanostructure with high surface hydroxyl group density and high performance in water treatment, Chem. Eng. J. 221 (2013) 342–352.

[74] S.E. Moradi, M.J. Baniamerian, Metal-oxide-modified nanostructured carbon application as novel adsorbents for chromate ion removal from water, Int. J. Mater. Res. 103 (2012) 743–748.

[75] M. Uygun, E. Feyzioğlu, E. Özçalışkan, M. Caka, A. Ergen, S. Akgöl, A. Denizli, New generation ion-imprinted nanocarrier for removal of Cr(VI) from wastewater, J. Nanoparticle Res. 15 (2013) 1833–1843.

[76] S.R. Chowdhury, E.K. Yanful, Arsenic and chromium removal by mixed magnetite e maghemite nanoparticles and the effect of phosphate on removal, J. Environ. Manage. 91 (2010) 2238–2247.

[77] Y. Cantu, A. Remes, A. Reyna, D. Martinez, J. Villarreal, H. Ramos, S. Trevino, C. Tamez, A. Martinez, T. Eubanks, J.G. Parsons, Thermodynamics, kinetics, and activation energy studies of the sorption of chromium(III) and chromium(VI) to a Mn3O4 nanomaterial, Chem. Eng. J. 254 (2014) 374–383.

[78] J.G. Parsons, J. Hernandez, C.M. Gonzalez, J.L. Gardea-torresdey, Sorption of Cr(III) and Cr(VI) to high and low pressure synthetic nano-magnetite (Fe3O4) particles, Chem. Eng. J. 254 (2014) 171–180.

[79] J.R. Rajabathar, A.K. Shukla, A. Ali, H.A. Al-Lohedan, Silver nanoparticle/r-graphene oxide deposited mesoporous-manganese oxide nanocomposite for pollutant removal and supercapacitor applications, Int. J. Hydrogen Energy. 42 (2017) 15679–15688.

[80] S. Sadeghi, F.A. Rad, A.Z. Moghaddam, A highly selective sorbent for removal of Cr(VI) from aqueous solutions based on Fe3O4/poly(methyl methacrylate) grafted Tragacanth gum nanocomposite: Optimization by experimental design, Mater. Sci. Eng. C. 45 (2014) 136–145.

[81] ATSDR, Priority List of Hazardous Substances, (2017). http://www.atsdr.cdc.gov/spl/ (accessed December 2, 2017).

[82] WHO, Guidelines for Drinking-water Quality, World Heal. Organ. (2011).

[83] WHO, Chromium in Drinking-water, World Heal. Organ. (2003). http://www.nap.edu/catalog/9038.html.

[84] W. Lu, J. Li, Y. Sheng, X. Zhang, J. You, L. Chen, One-pot synthesis of magnetic iron oxide nanoparticle-multiwalled carbon nanotube composites for enhanced removal of Cr(VI) from aqueous solution, J. Colloid Interface Sci. 505 (2017) 1134–1146.

[85] V.K. Gupta, R. Chandra, I. Tyagi, M. Verma, Removal of hexavalent chromium ions using CuO nanoparticles for water purification applications, J. Colloid Interface Sci. 478 (2016) 54–62.

[86] R. Nithya, T. Gomathi, P.N. Sudha, J. Venkatesan, S. Anil, S. Kim, Removal of Cr(VI) from aqueous solution using chitosan-g-poly(butyl acrylate)/silica gel nanocomposite, Int. J. Biol. Macromol. 87 (2016) 545–554.

[87] V. Sureshkumar, S.C.G.K. Daniel, K. Ruckmani, M. Sivakumar, Fabrication of chitosan – magnetite nanocomposite strip for chromium removal, Appl. Nanosci. 6 (2016) 277–285.

[88] L.J. Martínez, A. Muñoz-Bonilla, E. Mazario, F.J. Recio, F.J. Palomares, P. Herrasti, Adsorption of chromium(VI) onto electrochemically obtained magnetite nanoparticles, Int. J. Environ. Sci. Technol. 12 (2015) 4017–4024.

[89] M. Bagheri, H. Younesi, S. Hajati, S. Mehdi, Application of chitosan-citric acid nanoparticles for removal of chromium(VI), Int. J. Biol. Macromol. 80 (2015) 431–444.

[90] A.E. Chávez-Guajardo, J.C. Medina-Llamas, L. Maqueira, C.A.S. Andrade, K.G.B. Alves, C.P. de Melo, Efficient removal of Cr (VI) and Cu (II) ions from aqueous media by use of polypyrrole/maghemite and polyaniline/maghemite magnetic nanocomposites, Chem. Eng. J. 281 (2015) 826–836.

[91] R. Chen, L. Chai, Q. Li, Y. Shi, Y. Wang, A. Mohammad, Preparation and characterization of magnetic Fe3O4/CNT nanoparticles by RPO method to enhance the efficient removal of Cr(VI), Environ. Sci. Pollut. Res. 20 (2013) 7175–7185.

[92] H. Shen, S. Pan, Y. Zhang, X. Huang, H. Gong, A new insight on the adsorption mechanism of amino-functionalized nano-Fe3O4 magnetic polymers in Cu(II), Cr(VI) co-existing water system, Chem. Eng. J. 183 (2012) 180–191.

[93] Y.-G. Zhao, H.-Y. Shen, S.-D. Pan, M.-Q. Hu, Q.-H. Xia, Preparation and characterization of amino-functionalized nano-Fe3O4 magnetic polymer adsorbents for removal of chromium(VI) ions, J. Mater. Sci. 45 (2010) 5291–5301.

[94] I.G.B. Kaya, D. Duranoglu, U. Beker, B.F. Senkal, Development of Polymeric and Polymer-Based Hybrid Adsorbents for Chromium Removal from Aqueous Solution, Clean - Soil, Air, Water. 39 (2011) 980–988.

[95] J. Li, A. Kalam, A.S. Al-shihri, Q. Su, G. Zhong, G. Du, Monodisperse ceria nanospheres: Synthesis, characterization, optical properties, and applications in wastewater treatment, Mater. Chem. Phys. 130 (2011) 1066–1071.

[96] H. Zhu, S. Jia, T. Wan, Y. Jia, H. Yang, J. Li, L. Yan, C. Zhong, Biosynthesis of spherical Fe3O4/bacterial cellulose nanocomposites as adsorbents for heavy metal ions, Carbohydr. Polym. 86 (2011) 1558–1564.

[97] S. Sayin, M. Yilmaz, Synthesis of a new calixarene derivative and its immobilization onto magnetic nanoparticle surfaces for excellent extractants toward Cr(VI), As(V), and U(VI), J. Chem. Eng. Data. 56 (2011) 2020–2029.

[98] T.Y. Liu, L. Zhao, X. Tan, S.J. Liu, J.J. Li, Y. Qi, G.Z. Mao, Effects of physicochemical factors on Cr(VI) removal from leachate by zero-valent iron and a-Fe2O3 nanoparticles, Water Sci. Technol. 61 (2010) 2759–2768.

[99] S.J. Wu, T.H. Liou, F.L. Mi, Synthesis of zero-valent copper-chitosan nanocomposites and their application for treatment of hexavalent chromium, Bioresour. Technol. 100 (2009) 4348–4353.

[100] J. Hu, I.M.C. Lo, G. Chen, Comparative study of various magnetic nanoparticles for Cr(VI) removal, Sep. Purif. Technol. 56 (2007) 249–256.

Figure captions

Figure 1. *Eh-pH diagram of Cr-O-H system, in aqueous media, at 25ºC and 1 bar* [3].

Figure 2*. Pathways of chromium species in the water, including the interfaces with the atmosphere and sediment* [23].

Figure 3. *Proportion of chromium released to European water in 2015 by industrial sectors (E-PRTR).*

Figure 1

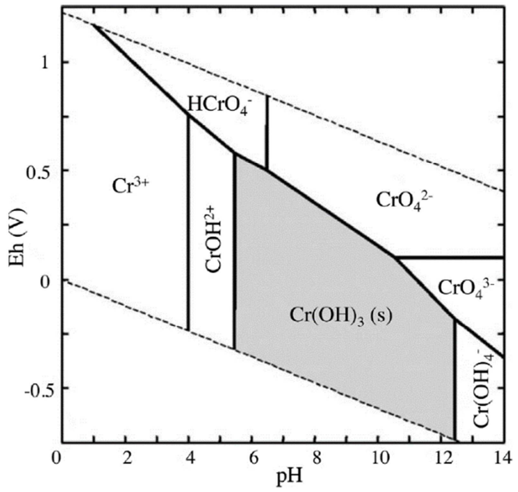
HCrO4-
Cr3+
CrOH2+
CrO42-
CrO43-
Cr(OH)3 (s)
Cr(OH)4-
Eh (V)
pH
1
0.5
0
-0.5
0
2
4
6
8
10
12
14

Figure 2

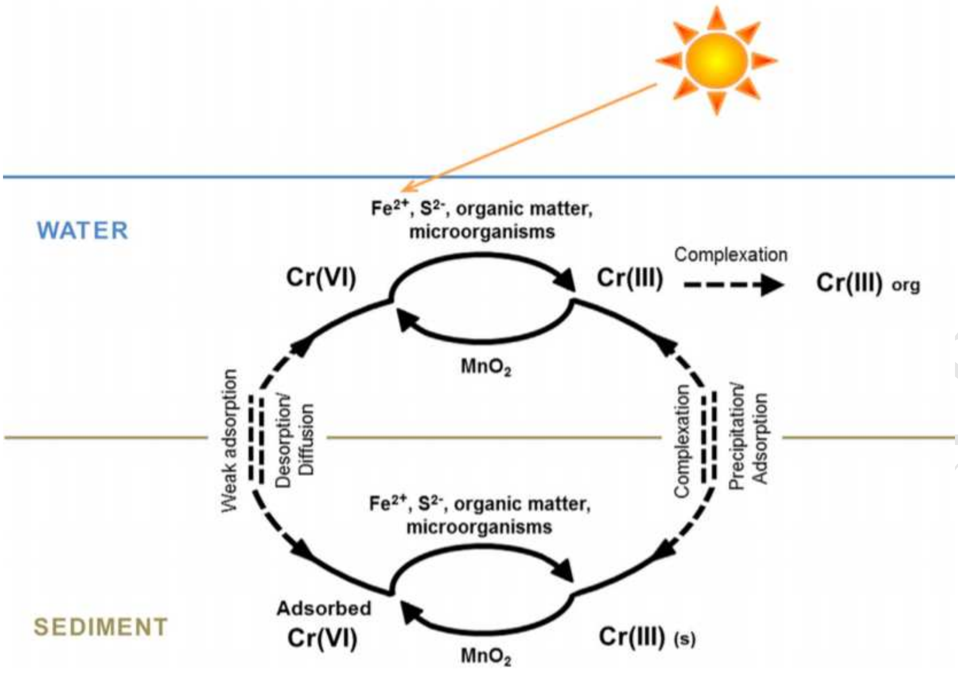
WATER
Fe2+, S2-, organic matter, microorganisms
Cr(VI)
Cr(III)
Complexation
Cr(III) org
MnO2
Weak adsorption
Desorption/ Diffusion
Complexation
Precipitation/ Adsorption
Fe2+, S2-, organic matter, microorganisms
SEDIMENT
Adsorbed Cr(VI)
MnO2
Cr(III) (s)

Figure 3

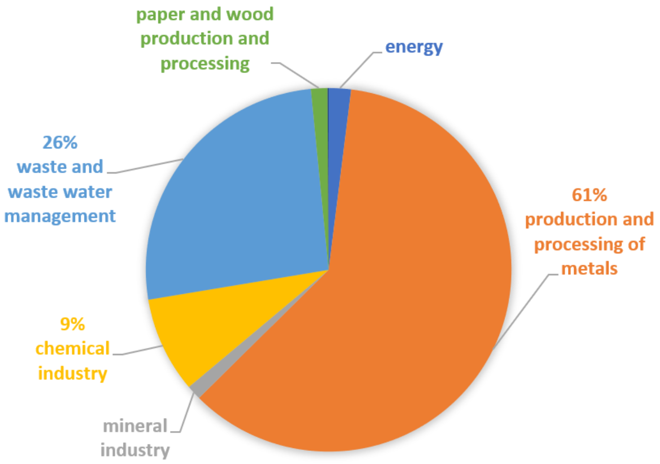
paper and wood production and processing
energy
26% waste and waste water management
61% production and processing of metals
9% chemical industry
mineral industry

Table legends

Table 1 - Legislated values regarding water contamination with chromium

Table 2 – Nanomaterials for Cr removal with respect to the conditions used as reported in the literature in the last 10 years (since 2007).

Table 1

Chromium species	Rank 2017[i]	Maximum allowed concentration (µg/L)		Concentration in surface water (µg/L)
		Residual waters	Drinking Water	
Chromium total	78		50[ii]	10 [iii]
Chromium, trivalent	351	3000[iv]		
Chromium, hexavalent	17			

i –ATSDR [81]; ii –WHO [82]; iii –WHO [83]; iv –France Guidelines for Metal Finishing Liquid Effluents [31].

Table 2

Reference	**Nanomaterial**	**Type of water**	**pH**	**Temperature (ºC)**	**Amount of sorbent (x10^{-3} mg/L)**	**Contact time (h)**	**Initial element concentration (x10^{-3} µg/L)**	**Cr starting specie**	**Uptake capacity (mg/g) or removal efficiency (%)**	**Type of system**
[40]	**Sn(II) oxy-hydroxides NPs** (pH synthesis) $Sn_6O_4(OH)_4$ (pH 2) $Sn_6O_4(OH)_4$ (pH 4) SnO_2 (pH 6) SnO_2 (pH 9) $Sn_3OSO_4(OH)_2$ (pH 2) $Sn_6O_4(OH)_4$ /SnO (pH 4) $Sn_6O_4(OH)_4$ /SnO (pH 6) $Sn_6O_4(OH)_4$ /SnO (pH 9)	Distilled water	6-8	10-30	0.025-0.75	0.016-48	0.010-5.0	Cr(VI)	~31 (30 ºC, $Sn_6O_4(OH)_4$ pH 2)	Mono elemental
	Sn(II) oxy-hydroxides NPs (pH synthesis)	Natural-like water	7.0-7.8	20			0.10	Cr(VI)	19 (pH 7, $Sn_6O_4(OH)_4$ pH 2)	Multi elemental
[42]	**Nano-ZrO_2** Nano zirconium oxide **Nano-ZrO_2-glu-CMC** Crosslinking of nanolayer carboxymethyl cellulose (CMC) onto the surface of nano zirconium oxide (Nano-ZrO_2) using glutaraldehyde	Distilled water	1.0-7.0	r.t. [f]	2.5	0.017-1.0	1040-10 400	Cr(III) Cr(VI)	187 (500 mg/L, Nano-ZrO_2-glu-CMC) 73 (500 mg/L, Nano-ZrO_2-glu-CMC)	Mono elemental
			7 2	r.t.	2.5	0.50	5200	Cr(III) Cr(VI)	11-26 Nano-ZrO_2 29-44 Nano-ZrO_2-glu-CMC 4-8 Nano-ZrO_2 14-27 Nano-ZrO_2-glu-CMC (depending on the type of interfering ion)	Multi elemental
[35]	**Pd/Fe_3O_4 NPs** Magnetite nanoparticles functionalized with palladium		3	Information not mentioned	5.0	8.0	20	Cr(VI) Total Cr	~60% ~60%	Multi elemental

[9]	**$K_2Mn_4O_9$** Rancieite type material		2-6	4-45	2.5	0.083-2.0	0.30-30	Cr(III) Cr(VI)	33% (pH 6)/ 41.8 (45ºC) 23% (pH 2) / 4.22 (4ºC)	Mono elemental
			5 2		2.5	1.0	0.30	Cr(III) Cr(VI)	~4-37% ~0-67% (depending on the type and concentration of interfering ion)	Multi elemental
[37]	**MNPLB** Lagerstroemia speciosa bark (LB) embedded magnetic nanoparticles	Double distilled water	1.09-7.02	15-40	0.1-0.7	0.17-2.0	50-500	Cr(VI)	739.7 (500 x10^3 µg/L)	Mono elemental
[84]	**MNP/MWCNTs** Magnetic iron oxide nanoparticle-multiwalled carbon nanotube composites	Ultrapure water	1.0-9.0	25-45	0.4-2.0	0-24	5.0-50	Cr(VI)	~98% (1000-2000 mg/L) 42.02 (45ºC)	Mono elemental
			2.0		1.0		10	Cr(VI)	~92-95% (depending on the type of interfering ion)	Multi elemental
[67]	**PAN-CNT/TiO_2-NH_2** Polyacrylonitrile (PAN) and carbon nanotube (CNTs)/titanium dioxide nanoparticles (TiO_2) functionalized with amine groups (TiO_2-NH_2) composite nanofibers		2-9	r.t. (20)	0.1-0.8	0-7	10-300	Cr(VI)	99.7% (6000 mg/L) 861.11 [a]	Mono elemental
[79]	**Meso-MnO_2** Mesoporous manganese oxide **AgNPs@meso-MnO_2** silver nanoparticles doped mesoporous manganese oxide **Ag/Graphene-meso-MnO_2** silver nanoparticle graphene deposited mesoporous manganese oxide nanocomposite	Milli-Q water	6	r.t.	6.7	24	50	Cr(VI)	~35%	Mono elemental

[41]	**CoFe$_2$O$_4$ NPs** Cobalt ferrite nanoparticles	Distilled water	2-12	25-55	2-12	0-4.0	75-150	Cr(VI)	98.45 % (55ºC, 75 x10^3 µg/L) 16.73 (55ºC)	Mono elemental
		Printing press wastewater	1-12	25-55	10	0-24	1637.5	Cr(VI)	~69%	Multi elemental
[39]	**MIO-MWCNTs** **MWCNTs** Multi-walled carbon nanotubes **MIO NPs** Magnetic iron oxide nanoparticles		2.6-7.3	5-60	1.0	0.25-4.0	5-100	Cr(VI)	12.61 (100 x10^3 µg/L, MIO-MWCNTs) 80.8% (5 x10^3 µg/L, MIO-MWCNTs)	Mono elemental
[52]	**CN-coated AC** Bituminous activated carbon (AC) coated with chitosan nanoparticles (CN) **CN-AC/DC** CN coated on AC by the dip coating method **CN-AC/WI** CN coated on AC by the wet impregnation method	Deionized water	5.0	Information not mentioned	1.0	0-24	0.10-100	Cr(VI)	77.52 (CN-AC/DC) 61.7% (0.1 x10^3 µg/L, CN-AC/DC)	Mono elemental
[8]	**n-Al$_2$O$_3$** γ-alumina nanoparticles modified with cetyl trimethyl ammonium bromide (CTAB)	Distilled water	2.0-10.0	30-60	4-24	0-1.5	5-25	Cr(VI)	94% (5 x10^3 µg/L, pH 2.03, 18 340 mg NPs/L) 18.716 ^{b} (25 x10^3 µg/L)	Mono elemental
[85]	**CuO NPs** Copper(II) oxide nanoparticles	Double distilled water	2-10	25-45	0.4-5	0-3.0	10-150	Cr(VI)	96.3% (10 x10^3 µg/L) 86.25 (400 mg/L)	Mono elemental
[72]	**IONPs** Magnetic iron oxide nanoparticles **MIONPs** EDTA-modified magnetic iron oxide nanoparticles		2	r.t.	0.0050-0.030	0-18	200-1000	Cr(VI)	99.90% / 499.5 (30 mg/L, MIONPs) 34.06% / 170.33 (30 mg/L, IONPs)	Mono elemental
[68]	**Ti-AX**	Synthetic	8	Information	0.60	168	0.10	Cr(VI)	88%	Multi

	Titanium dioxide nanoparticles precipitated in anion exchange resins	groundwater		not mentioned						elemental
[86]	**Cs-g-PBA/SG** Chitosan-g-poly(butylacrylate)/ silica gel nanocomposite		3-9	r.t.	10-60	1.0-6.0	62.5-1000	Cr(VI)	98% (62.5-125 x10^3 μg/L) 55.71	Mono elemental
[87]	**Chitosan–Fe_3O_4 nanocomposite strip** Chitosan–magnetite nanocomposite strip	Deionised water	Information not mentioned	Information not mentioned	1 cm x 1 cm 0.010 L	0.17, 0.30, 0.83, 1.2, 1.5, 1.8, 2.2	260	Cr(VI)	~15-92.33%	Mono elemental
[47]	**TF-SCMNPs** Thiol-functionalized mesoporous silica-coated magnetite nanoparticles (**Fe_3O_4 NPs**)	Distilled water	3-10	r.t. (25)	0.080-0.40	0.083-24	8	Cr(III)	42% (pH 10, 400 mg/L) 1.119	Mono elemental
[43]	**Fe-Cu binary oxide NPS**	Milli-Q water	1-9	r.t. (25)	0.10-2.5	1.0	1-25	Cr(VI)	~100% (100 mg/L, 1 x10^3 μg/L) 71.43	Mono elemental
[51]	**MIN** Magnetic iron oxide nanoparticles **MIN-TW** Magnetic iron oxide nanoparticles/tea waste composite **MIN-SB** Magnetic iron oxide nanoparticles/sugarcane bagasse composite	Deionized water	2-7	30	0.50-1.25	0.083-2.0	50-300	Cr(III)	98.27% (MIN-SB, 1h, 1125 mg/L) 518.134 ^{d} (MIN-SB, 0.75 h)	Mono elemental
	MIN MIN-TW MIN-SB	Deionized water						Cr(III)	~229-243 ~228-240 ~243-247 (depending on the type of interfering ion)	Multi elemental
[36]	**ST/Mag NPs** Spent tea-supported magnetite nanoparticles	Double-distilled water	2-8	r.t. (20)	0.10-11.0	0.033-4.0	5-300	Cr(VI)	~100% (5 x10^3 μg/L) 30.03	Mono elemental
		Synthetic saline wastewater	2	20	3.0	1.0	10	Cr(VI)	78.3-99.9% 1.09-1.39 (depending on the concentration of interfering ions)	Multi elemental

[44]	**Fe_3O_4 NPs** Magnetic magnetite nanoparticles	Double distilled water	2-10	25-45	1.0-4.0	0-24	2-100	Cr(VI)	~75% (4000 mg/L) 34.9 (45ºC)	Mono elemental
[38]	**ESH** Electrospun hematite nanofiber **ESH@MS-60** Electrospun hematite nanofiber/mesoporous silica core/shell **ESH@MS-60-NH_2** Electrospun hematite nanofiber/mesoporous sílica functionalized with amine group		3-6	25	0.25	2.0	5.2-104	Cr(III)	343 (pH 5.4, ESH@MS-60-NH_2)	Mono elemental
[45]	**$CaFe_2O_4$ NPs** Calcium ferrite nanoparticles	Ultrapure deionized water	2-6	r.t.	0.0625-1.0	0.033-1.7	30-250	Cr(IV)	340 (62.5 mg/L) 99% (pH 2 / 30 x10^3 µg/L)	Mono elemental
[46]	**$MnFe_2O_4$ NPs** Manganese ferrite nanoparticles	Real wastewater from galvanotechnic industry	2	r.t.	0.5-6.0	0.17-24	50-250	Total Cr	334.80 (500 mg/L) 71.37% (1500 mg/L)	Multi elemental
[70]	**Fe_3O_4 NPs** Magnetite nanoparticles	Distilled water	7	20	0.10-1.0	0.083-24	0.25	Cr(VI)	~2.4 (24 h)	Mono elemental
		Natural-like water	5-8	20	0.10-1.0	0.083-24	0.050-1.0	Cr(VI)	~100% (pH 6.5, 3 h / pH 7.0, 4 h) 4 (pH 5)	Multi elemental
[88]	**Fe_3O_4 NPs** Magnetite nanoparticles		1.5-4.5	10-75	0.50-2.0	0-2.0	0-160	Cr(VI)	~26 (2000 mg/L)	Mono elemental
[89]	**CS–CA NPs** Chitosan–citric acid nanoparticles **CS NPs** Chitosan nanoparticles	De-ionized water	2-6	25-45	0.50-5.0	0-2.0	10-110	Cr(VI)	94.46% (70 x10^3 µg/L) 38.51 (500 mg/L)	Mono elemental
[65]	**CuO NPs** Cupric oxide nanoparticles	De-ionized double distilled water	2.0-10.0	20-60	0.25-2.5	0-5.8	5-50	Cr(VI)	98.8% 50.0 (250 mg/L)	Mono elemental
[58]	**TiO_2 NPs** Titania nanoparticles	Deionized (MilliQ) water	2.0-12.0	28	0.010-0.50	0.083-0.75	5-100	Cr(VI)	85.85 (20 x10^3 µg/L)	Mono elemental

[56]	**BnM** Biogenic nano-magnetite	Ultrapure water	12	20	0.75 Anoxic	0-350	Model solution	Cr(VI)	32	Mono elemental
		Contaminated groundwater	11.9	20	0.66 Anoxic 0.66 Oxic	0-200	16.69	Cr(VI)	24 7	Multi elemental
[48]	**PAA@VTES@Fe_3O_4 NPs** Magnetite nanoparticles coated with silane coupling agent (VTES) grafted with polyacrylic acid (PAA)	Ultrapure water	2-6	20-40	1.0-6.5	0-24	170	Cr(III)	92.5% (pH 6, 5000-6500 mg/L) 80.6 (40ºC)	Mono elemental
		Tannery effluent	6		5.0	4.0	170	Total Cr	94.0%	Multi elemental
[64]	**Fe_3O_4 NPs** Magnetite nanoparticles	Deaerated deionized water	2-10	25-45	1.0-5.0	0-3.0	0-120	Cr(VI)	100% (pH 2, 4000 mg/L, 20 x10^3 µg/L, 40ºC)	Mono elemental
							20	Cr(VI)	80-100% (depending on the type and concentration of interfering anion)	Multi elemental
[55]	**Fe_3O_4 nanospheres** Mesoporous magnetite nanospheres	Double distilled water	2-7	25-45	1.0-3.0	1.0-72	5–100	Cr(VI)	44% (1h, 2000 mg/L) 8.90 (45ºC)	Mono elemental
		Groundwater	4	25	2.0	48	10	Cr(VI)	65%	Multi elemental
[90]	**PPY/γ-Fe_2O_3** Polypyrrole/maghemite **PANI/γ-Fe_2O_3** Polyaniline/maghemite	Deionized water	2.0-10.0	r.t.	0.2	0.083-2	2.5-100	Cr(VI)	~100% (pH 2, 2.5 mg/L) 208.8 (PPY/γ-Fe_2O_3, pH 2, 100 mg/L)	Mono elemental
[80]	**P(MMA)-g-TG-MNPs** Poly(methyl methacrylate) grafted Tragacanth gum modified Fe_3O_4 magnetic nanoparticles	Deionized water	2.0-7.0	25	3.0	0-4.2	1-30	Cr(VI)	~ 50-100% (pH 2) 7.84 (30 mg/L)	Mono elemental
							20	Cr(VI)	91.7-98.4% (without interfering ions)	Multi elemental
		Electroplating wastewater	5.5				10-10.020	Cr(VI)	89.0-96.2% (10 mg/L)	
		Underground water	5.5				0.100-0.150	Cr(VI)	59.8-97.8% (0.100 mg/L)	

[78]	**Fe_3O_4 NPs** Magnetite nanoparticles		2-6		2.5	0.083-1.0	0.10-10	Cr(III) Cr(VI)	100% (pH 4, 0.25 h) / 0.555 100% (pH 4, 0.33 h) / 1.705 (depending on the material type)	Mono elemental
					2.5	1.0	0.10	Cr(III) Cr(VI)	~60-100% ~25-100 % (depending on the material type and on the type and concentration of interenfence anion)	Multi elemental
[77]	**Mn_3O_4** Manganese oxide nanomaterial		2-6	4-45	2.5	0.17-4.0	0.30-1000	Cr(III) Cr(VI)	90% (pH 2)/ 54.4 (45ºC) 85% (pH 2) / 5.8 (45ºC)	Mono elemental
[49]	**PMMNs** Polyacrylamide modified iron oxide nanoparticles		1-8	30	20	0-2.0	50-1000	Cr(VI)	~99% (pH 3, 100 x10^3 µg/L) 35.186	Mono elemental
			3	30		0.67	100	Cr(VI)	~94-98% (depending on the type and concentration of salt)	Multi elemental
[71]	**Fe_3O_4 NPs** Iron oxide magnetic nanoparticles	Artificial wastewater	3-9	25	250-1500 mg (volume not mentioned)	0.25-1.5	250-1000	Cr(III)	99.9% (pH 9)	Mono elemental
[59]	**NiO NPs** Mesoporous nickel oxide nanoparticles	Distilled water	4.7-9	30	1.0-7.0	0-0.83	10-50	Cr(VI)	~100% (10 x10^3 µg/L, 7000 mg/L) / ~5 (50 x10^3 µg/L)	Mono elemental
[75]	**Cr(VI)-imprinted poly(HEMAH) NPs** Chromium(VI)-imprinted hydroxyethylmethacrylate (HEMA) polymeric nanoparticles	Milli-Q ultrapure water	2-6	25	Information not mentioned	0-2	1000 -11 000	Cr(VI)	3830.58	Mono elemental
[73]	**TiO_2 NPs** Titania nanoparticles		4.0	25	0.10	0-2.5	0-80	Cr(VI)	21.92	Mono elemental
[50]	**Fe_3O_4-loaded seeds** Magnetite nanoparticles loaded natural seeds sabja		2	Information not mentioned	1000 mg (volume not mentioned)	0, 0.25, 0.50, 0.75, 1.0, 1.5, 2.0	1 5 20 30 50	Cr(VI)	~100% 97% ~85% ~80% ~75%	Mono elemental
							50	Cr(VI)	80%	Multi elemental
[91]	**Fe_3O_4/CNT NPs** Carbon nanotubes loaded with magnetite nanoparticles		2-12	20-80	1.0	0.083-120	100-1000	Cr(VI)	95% (pH 2) / 60 (pH 2)	Mono elemental

[69]	**Fe_3O_4 NPs** Iron(II/III) oxide or magnetite or ferrite nanoparticles **$MnFe_2O_4$ NPs** Magnanese(II) iron (III) oxide or jacobsite or manganese ferrite nanoparticles		2-10	4-50	2.5	1.0	0.30-100	Cr(III) Cr(VI)	100% (Fe_3O_4, pH 6/7) 10.638 100% ($MnFe_2O_4$, pH 2/3) 3.455	Mono elemental
[60]	**Magnetic PS-EDTA resin** Magnetic chelating resin with EDTA functionality		2-12	30	0.20-2.0	0.083-10	5-1000	Cr(VI)	100 % (pH 4, 10 h, 1000 mg/L, 5-40 x10^3 µg/L) 250.00	Mono elemental
[61]	Semicarbazone derivatives of calix[4]arene immobilized onto magnetic nanoparticles (Fe_3O_4): **MN-C1**, **MN-C2**, **MN-C3**	Deionized water	1.5-4.5	30	2.5	1.0	5.2-20.8	Cr(VI)	90% (MN-C2, pH 1.5)	Mono elemental
[74]	**NC** Nanoporous carbon **Ni-NC** Nickel oxide onto nanoporous carbon **Fe-NC** Iron oxide onto nanoporous carbon	Ultrapure water	2-10	20, 30, 40	0.20	0-6.0	10-100	Cr(VI)	60.8 (Fe-NC, r.t.)	Mono elemental
[92,93]	**NH_2-NMPs** Amino-functionalized nano-Fe_3O_4 magnetic polymer adsorbents EDA-NMPs DETA-NMPs TETA-NMPs TEPA-NMPs	Ultrapure water	2.0-9.0	25-65	1.25	0-90	50-1000	Cr(VI)	99.9% (TEPA-NMPs, pH 2.0, 50 mg/L) 370.37 (TEPA-NMPs, pH 2.0, 35ºC)	Mono elemental
	EDA-NMPs DETA-NMPs TETA-NMPs TEPA-NMPs		2.0-4.0	35	1.25	12	200, 400, 1000	Cr(VI)	34.19-76.70% (pH 3.5, 200 mg/L) 98.79-200.18 (pH 2.0, 1000 mg/L) 24.96-57.85% (pH 3.5, 200 mg/L) 82.67-139.87 (pH 4.0, 1000 mg/L) 45.24-81.90% (pH 3.5, 200 mg/L) 120.63-201.74 (pH 2.5, 1000 mg/L) 48.75-92.04% (pH 2.0, 1000 mg/L) 125.83-368.13 (pH 2.0, 1000 mg/L)	Multi elemental

[66]	**PEI-γ-Fe_2O_3@Fe_3O_4 NPs** Polyethylenimine-modified magnetic nanoparticles		2-9	15-35	4.0	0-2.0	50-500	Cr(VI)	98.2% (100 x10^3 μg/L) 83.33 (15ºC)	Mono elemental
			2.2	25	4.0	0.50	100	Cr(VI)	~98-100%	Multi elemental
		Wastewater			2.67	0.50	37.98	Cr(VI)	99.0%	
[94]	**GMDFe** Nanosized ferric oxide loaded glycidyl methacrylatebased polymer		2-10	r.t. (25)	4.0	Equilibrium time	30	Cr(VI)	98% (24 h) 163.47 (pH 2)	Mono elemental
[95]	**CeO_2 NPs** Monodisperse ceria nanospheres	Simulated wastewater	Information not mentioned	r.t.	1.0	0-2.0	4.8 8	Cr(VI)	94.5% / ~4.5 94.1% / 7.52	Mono elemental
[96]	**Fe_3O_4/BC nanocomposites** Magnetite/bacterial cellulose nanocomposites	Deionized water	Information not mentioned	25	2.5	2	0, 20, 40, 60, 80, 100, 150, 200	Cr(III)	~25-70% (20 mg/L) ~0-20 (200 mg/L)	Mono elemental
[57]	**magMCM-41** Magnetic MCM-41 nanosorbents	Deionized, distilled water	2-7	r.t. (25)	1.0	Information not mentioned	106-156	Cr(VI)	98.8 (pH 2), 83.2 (pH 5)	Mono elemental
		Deionized, distilled water	2-5					Cr(VI)	67.6	Multi elemental
			5.0				156		67.6	
		Tap water	5.2				114	Cr(VI)	46.8	
		Mountain stream water	5.4				122	Cr(VI)	31.2	
			2, 5, 8						97% (pH 2), 97% (pH 5), 86% (pH 8)	
		River water	5.5				106	Cr(VI)	41.6	
[97]	**BHCB-MN** 5,11,17,23-tetra-tert-butyl-25,27-di(benzhydrazidylmethoxy)-26,28-dihydroxy-calix[4]arene immobilized silica-based magnetic nanoparticles	Deionized water	1.5	25	2.5	1	5.2	Cr(VI)	66%	Mono elemental
			2.5						~64%	
			3.5						11%	
			4.5						~0%	

[62]	**$Cu_2CO_3(OH)_2$ NPs** Malachite nanoparticles	Milli-Q water	4-9	10-40	5.0-20	1-16	20-500	Cr(VI)	82.2 75% (pH 5, 50 x10^3 µg/L)	Mono elemental
			5				50	Cr(VI)	70%	Multi elemental
[63]	**NHTO** Nanoparticles of hydrous titanium(IV) oxide	Distilled water	2.0	30	1000-3000 mg (packed column)	0.013-0.026	8.0-32.0	Cr(VI)	12.94 ^{e} (32.0 x10^3 µg/L)	Mono elemental
		Industrial effluent wastewater	2.06	30	4000	0.026	15.67	Cr(VI)	~100%	Multi elemental
[98]	**α-Fe_2O_3 NPs** Hematite nanoparticles	Dilute simulated landfill leachate	3-8	20-35	0.50-3.0	0-24	20-200	Cr(VI)	~90% (pH 3)	Mono elemental
			6.7				20	Cr(VI)	~50%	Multi elemental
[76]	**Fe_3O_4-γ-Fe2O3 NPs** Magnetite-maghemite nanoparticles	De-ionized water	2-14	r.t.	0.40	0.17-4	1-2	Cr(VI)	96% (pH 2, 1 x10^3 µg/L) 4.45 (pH 2, 2 x10^3 µg/L)	Mono elemental
			4		0.40			Cr(VI)	35-90%	Multi elemental
[99]	**Ch-(Cu^0)** Zero-valent copper-chitosan nanocomposites	Deionized water	2.85 4.85	25	2	24	50	Cr(VI)	95.58% 94.2%	Mono elemental
[100]	Magnetic NPs: $MnFe_2O_4$ $MgFe_2O_4$ $ZnFe_2O_4$ $CuFe_2O_4$ $NiFe_2O_4$ $CoFe_2O_4$	Milli-Q water	2.0-9.3	22.5	5.0	0-1.0	20-100	Cr(VI)	100% ($MnFe_2O_4$, 0.083 h)	Mono elemental

[a]Nonlinear Pseudo-second-order model. [b]Pseudo-second-order model. [c]Langmuir type 4 capacity. [d]Langmuir type 1 capacity. [e]Thomas model column capacity. [f]Room temperature.

Note that,
the conditions that are shaded correspond to the best uptake capacity or removal efficiency obtained;
in general, when the type of water is not referred, the authors may have used distilled or milli-Q water;
in the column correspondent to “Cr starting specie”, total chromium concentration was quantified in the works that refer it; in the other works no mention is made regarding the specie or if it is total concentration;
in the column correspondent to “Uptake capacity (mg/g) or removal efficiency (%)”, when the value does not present units, it is the uptake capacity; otherwise, it is the removal efficiency;
the value presented in parentheses in the column “Uptake capacity (mg/g) or removal efficiency (%)” corresponds to the condition that gave rise to the value of uptake capacity or removal efficiency presented;

the uptake capacity values which do not presented a subscript were obtained either experimentally or by Langmuir model;
sometimes, the authors refer to experimental conditions of experiments whose results they do not present;
from column “Type of water” until “Cr starting specie”, the conditions mentioned are the same for the below lines

Supplementary Information

Table 2 – Nanomaterials for Cr removal with respect to the conditions used as reported in the literature in the last 10 years (since 2007).

Reference	Nanomaterial	Type of water	pH	Temperature (°C)	Amount of sorbent ($x10^{-3}$ mg/L)	Contact time (h)	Initial element concentration ($x10^{-3}$ µg/L)	Cr starting specie	Uptake capacity (mg/g) or removal efficiency (%)	Type of system
[40]	**S n(II) oxy-hydroxides NPs** (pH synthesis)	Distilled water	6-8	10-30	0.025-0.75	0.016-48	0.010-5.0	Cr(VI)	~31 (30 ºC, $Sn_6O_4(OH)_4$ pH 2)	Mono elemental
	$Sn_6O_4(OH)_4$ (pH 2)		6, 7, 8	20	0.025-0.75	24	0.25-5.0		29.359 (pH 6), 23.440 (pH 7), 21.359 (pH 8)	
	$Sn_6O_4(OH)_4$ /SnO (pH 4)		6, 7, 8						10.354 (pH 6), 8.112 (pH 7), 6.990 (pH 8)	
	$Sn_6O_4(OH)_4$ (pH 2)		7	20			0.010		19	
	$Sn_6O_4(OH)_4$ (pH 4)								10	
	SnO_2 (pH 6)								<0.5	
	SnO_2 (pH 9)								<0.5	
	$Sn_3OSO_4(OH)_2$ (pH 2)								6.1	
	$Sn_6O_4(OH)_4$ /SnO (pH 4)								5.2	
	$Sn_6O_4(OH)_4$ /SnO (pH 6)								5.2-6.1	
	$Sn_6O_4(OH)_4$ /SnO (pH 9)								5.2-6.1	
	$Sn_6O_4(OH)_4$ (pH 2)		7	10, 20, 30	0.20	0.016-48	5.0		~19 (10ºC), 27 (20ºC), 31 (30ºC)	
	Sn(II) oxy-hydroxides NPs (pH synthesis)	Natural-like water	7.0-7.8	20			0.10	Cr(VI)	19 (pH 7, $Sn_6O_4(OH)_4$ pH 2)	Multi elemental
	$Sn_6O_4(OH)_4$ (pH 2)		7.0	20			0.010		19	
			7.8						18.5	
	$Sn_6O_4(OH)_4$ (pH 4)		7.0						7.0	
	$Sn_6O_4(OH)_4$ /SnO (pH 4)		7.0						4.0	
	$Sn_6O_4(OH)_4$ /SnO (pH 9)		7.0						4.8	

[42]	**Nano-ZrO$_2$** Nano zirconium oxide **Nano-ZrO$_2$-glu-CMC** Crosslinking of nanolayer carboxymethyl cellulose (CMC) onto the surface of nano zirconium oxide (Nano-ZrO$_2$) using glutaraldehyde	Distilled water	1.0-7.0	r.t. [f]	2.5	0.017-1.0	1040-10 400	Cr(III) Cr(VI)	187 (500 mg/L, Nano-ZrO$_2$-glu-CMC) 73 (500 mg/L, Nano-ZrO$_2$-glu-CMC)	Mono elemental
			1.0-7.0	r.t.	2.5	0.50	5200	Cr(III) Cr(VI)	3-26 Nano-ZrO$_2$ (pH 7) 44-58 Nano-ZrO$_2$-glu-CMC (pH 7) 2-6 Nano-ZrO$_2$ (pH 1-2) 19-35 Nano-ZrO$_2$-glu-CMC (pH 1-2)	
				r.t.	2.5	0.017, 0.083, 0.17, 0.25, 0.33, 0.42, 0.50, 0.67, 0.83, 1.0	5200	Cr(III) Cr(VI)	26 Nano-ZrO$_2$ (1 h) 62 Nano-ZrO$_2$-glu-CMC (1 h) 6 Nano-ZrO$_2$ (1 h) 37 Nano-ZrO$_2$-glu-CMC (1 h)	
				r.t.	0.50, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10	0.50	5200	Cr(III) Cr(VI)	94 Nano-ZrO$_2$ (500 mg/L) 187 Nano-ZrO$_2$-glu-CMC (500 mg/L) 10 Nano-ZrO$_2$ (500 mg/L) 73 Nano-ZrO$_2$-glu-CMC (500 mg/L)	
			7 2	r.t.	2.5	0.50	1040, 2080, 3120, 4160, 5200, 6240, 7279, 8319, 9349, 10 400	Cr(III) Cr(VI)	62 Nano-ZrO$_2$ (10 400 x10^3 µg/L) 89 Nano-ZrO$_2$-glu-CMC (10 400 x10^3 µg/L) 18 Nano-ZrO$_2$ (10 400 x10^3 µg/L) 54 Nano-ZrO$_2$-glu-CMC (10 400 x10^3 µg/L)	
			7 2	r.t.	2.5	0.50	5200	Cr(III) Cr(VI)	11-26 Nano-ZrO$_2$ 29-44 Nano-ZrO$_2$-glu-CMC 4-8 Nano-ZrO$_2$ 14-27 Nano-ZrO$_2$-glu-CMC (depending on the type of interfering ion)	Multi elemental

[35]	**Pd/Fe_3O_4 NPs** Magnetite nanoparticles functionalized with palladium		3	Information not mentioned	5.0	8.0	20	Cr(VI) Total Cr	~60% ~60%	Multi elemental
[9]	**$K_2Mn_4O_9$** Rancieite type material		2-6	4-45	2.5	0.083-2.0	0.30-30	Cr(III) Cr(VI)	33% (pH 6)/ 41.8 (45ºC) 23% (pH 2) / 4.22 (4ºC)	Mono elemental
			2, 3, 4, 5, 6	r. t.	2.5	1.0	0.30	Cr(III) Cr(VI)	~5-33% (pH 6) ~3-23% (pH 2)	
			5 2	4, 25, 45	2.5	0.083, 0.17, 0.25, 0.50, 1.0, 1.5, 2.0	30	Cr(III) Cr(VI)	21.7 (4ºC), 36.5 (25ºC), 41.8 (45ºC) 4.22 (4ºC), 4.08 (25ºC), 3.25 (45ºC)	
			5 2		2.5	1.0	0.30	Cr(III) Cr(VI)	~4-37% ~0-67% (depending on the type and concentration of interfering ion)	Multi elemental
[37]	**MNPLB** Lagerstroemia speciosa bark (LB) embedded magnetic nanoparticles	Double distilled water	1.09-7.02	15-40	0.1-0.7	0.17-2.0	50-500	Cr(VI)	739.7 (500 x10^3 µg/L)	Mono elemental
			2.05	35	0.4	0.17, 0.50, 0.83, 1.2, 1.5, 1.83, 2.0	100		234.3 (0.17h), 237.2 (0.50h), 239.7 (0.83h), 243.1 (1.2h), 249.7 (1.5h), 249.7 (1.83h), 249.8 (2.0h)	
			2.05	35	0.4	1.5	50, 100, 200, 250, 300, 500		124.9 (50 x10^3 µg/L), 249.7 (100 x10^3 µg/L), 350.4 (200 x10^3 µg/L), 384.5 (250 x10^3 µg/L), 444.0 (300 x10^3 µg/L), 739.7 (500 x10^3 µg/L)	
			2.05	35	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7	1.5	100		675.2 (100 mg/L), 394.7 (200 mg/L), 315.2 (300 mg/L), 249.7 (400 mg/L), 199.9 (500 mg/L), 166.6 (600 mg/L), 142.8 (700 mg/L)	
			1.09, 2.05, 3.0, 4.02, 5.04, 6.07, 7.02	35	0.4	1.5	100		249.7 (pH 1.09), 249.7 (pH 2.05), 242.3 (pH 3.0), 235.5 (pH 4.02), 234.6 (pH 5.04), 231.6 (pH 6.07), 225.5 (pH 7.02)	

			2.05	15, 20, 25, 30, 35, 40	0.4	1.5	100		197.4 (15ºC), 208.0 (20ºC), 239.9 (25ºC), 246.3 (30ºC), 249.7 (35ºC), 249.7 (40ºC)	
[84]	**MNP/MWCNTs** Magnetic iron oxide nanoparticle-multiwalled carbon nanotube composites	Ultrapure water	1.0-9.0	25-45	0.4-2.0	0-24	5.0-50	Cr(VI)	~98% (1000-2000 mg/L) 42.02 (45ºC)	Mono elemental
			1, 2, 3, 4, 5, 6, 7, 8, 9	25	1.0	4.0	5.0		~15-95% (pH 2)	
			2.0	25	0.4, 0.6, 0.8, 1.0, 1.2, 1.6, 2.0	4.0	5.0		~61-98% (1000-2000 mg/L)	
			2.0	25, 35, 45	1.0	24	5.0, 10, 20, 30, 40, 50		22.22 (25ºC), 39.68 (35ºC), 42.02 (45ºC) (depending on the material type)	
			2.0	25	1.0	0.083-6.0	5.0, 10, 15		4.964 (5 x10^3 μg/L), 9.457 (10 x10^3 μg/L), 13.43 (15 x10^3 μg/L) (depending on the material type)	
			2.0		1.0		10	Cr(VI)	~92-95% (depending on the type of interfering ion)	Multi elemental
[67]	**PAN-CNT/TiO_2-NH_2** Polyacrylonitrile (PAN) and carbon nanotube (CNTs)/titanium dioxide nanoparticles (TiO_2) functionalized with amine groups (TiO_2-NH_2) composite nanofibers		2-9	r.t. (20)	0.1-0.8	0-7	10-300	Cr(VI)	99.7% (6000 mg/L) 861.11 [a]	Mono elemental
			2, 3, 4, 5, 7, 9	20	0.5		10		~65-99% (pH 2)	
			2	20, 40, 60	0.5		10-300		732 (20ºC), 704.7 (40ºC), 584.8 (60ºC)	
			2	20		0-7	10 20 30 50 80 100 200 300		26.67 [a] 53.88 [a] 78.95 [a] 137.30 [a] 217.47 [a] 276.47 [a] 550.87 [a] 861.11 [a]	
			2		0.1, 0.2, 0.4, 0.6, 0.8	0.67	100		55.2-99.7% (6000 mg/L)	

[79]	**Meso-MnO_2** Mesoporous manganese oxide	Milli-Q water	6	r.t.	6.7	24	50	Cr(VI)	~35%	Mono elemental
	AgNPs@meso-MnO_2 silver nanoparticles doped mesoporous manganese oxide								98% / 460	
	Ag/Graphene-meso-MnO_2 silver nanoparticle graphene deposited mesoporous manganese oxide nanocomposite								68% / 140	
[41]	**$CoFe_2O_4$ NPs** Cobalt ferrite nanoparticles	Distilled water	2-12	25-55	2-12	0-4.0	75-150	Cr(VI)	98.45 % (55ºC, 75 x10^3 µg/L) 16.73 (55ºC)	Mono elemental
				25	10	0-4.0	75, 100, 125, 150		65.50-91.76% (75 x10^3 µg/L)	
					2, 4, 6, 8, 10, 12				~62-93% (12 x10^3 mg/L)	
			2, 4, 6, 8, 10, 12	25	10		75		50.0-94.14% (pH 2)	
				25, 40, 55	10	2.0	75 100 125 150		91.76-98.45% (55ºC) 84.57-93.45% (55ºC) 75.20-85.94% (55ºC) 65.50-74.91% (55ºC)	
			6	25, 40, 55	10	2.0			10.53 (25ºC), 10.98 (40ºC), 16.73 (55ºC)	
		Printing press wastewater	1-12	25-55	10	0-24	1637.5	Cr(VI)	~69%	Multi elemental
			0.98	25	10	0-24	1637.5		~69 %	
			1, 2, 4, 5, 10, 12	25	10		1637.5		~36-89% (pH 10/12)	
			2	25, 40, 55	10	2.0	1637.5		46.44-64.56% (55 ºC)	

[39]	**MIO-MWCNTs** **MWCNTs** Multi-walled carbon nanotubes **MIO NPs** Magnetic iron oxide nanoparticles		2.6-7.3	5-60	1.0	0.25-4.0	5-100	Cr(VI)	12.61 (100 x10^3 µg/L, MIO-MWCNTs) 80.8% (5 x10^3 µg/L, MIO-MWCNTs)	Mono elemental
	MIO-MWCNTs MWCNTs MIO NPs		3	30	1.0	0.25, 0.50, 0.75, 1.0, 2.0, 3.0, 4.0	10		4.54 – 5.93 (4 h) 4.80 (4 h) 5.27 (4 h)	
	MIO-MWCNTs		3	30	1.0	4.0	5-100		12.6-80.8% (5 x10^3 µg/L) 4.04-12.61 (100 x10^3 µg/L)	
	MIO-MWCNTs		3	5, 15, 30, 45, 60	1.0	0.25, 0.50, 0.75, 1.0, 2.0, 3.0, 4.0	10		5.47-6.64 (5ºC)	
	MIO-MWCNTs		2.6-7.3	30	1.0		10		2.13-5.70 (pH 3)	
					1.0		5-100		11.256	
[52]	**CN-coated AC** Bituminous activated carbon (AC) coated with chitosan nanoparticles (CN) **CN-AC/DC** CN coated on AC by the dip coating method **CN-AC/WI** CN coated on AC by the wet impregnation method	Deionized water	5.0	Information not mentioned	1.0	0-24	0.10-100	Cr(VI)	77.52 (CN-AC/DC) 61.7% (0.1 x10^3 µg/L, CN-AC/DC)	Mono elemental
			5.0		1.0	0-24	0.10-100		61.35 CN NPs 57.47 CN-AC/WI 77.52 CN-AC/DC 38.5-61.7% CN-AC/DC (0.1 x10^3 µg/L)	
			5.0		1.0	0-24	10		4.66 CN-AC/WI 4.84 CN-AC/DC	
[8]	**n-Al_2O_3** γ-alumina nanoparticles modified with cetyl trimethyl ammonium bromide (CTAB)	Distilled water	2.0-10.0	30-60	4-24	0-1.5	5-25	Cr(VI)	94% (5 x10^3 µg/L, pH 2.03, 18 340 mg NPs/L) 18.716 [b] (25 x10^3 µg/L)	Mono elemental
			2, 4, 6, 8, 10						~46-94% (pH 2)	
			2			0-1.5	5 10 15		4.707 8.415 12.155 [b]	

							20		15.933 ^{b}	
							25		18.716 ^{b}	
									~40-94% (5 x10^3 µg/L, 1h)	
			2		4, 8, 12, 16, 20, 24				~52-94% (20 000-24 000 mg/L)	
			2	20			5, 10, 15, 20, 25		~64-94% (5 x10^3 µg/L) / 0.8952	
				30					~54-87% (5 x10^3 µg/L) / 0.8204	
				40					~50-70% (5 x10^3 µg/L) / 1.0149	
				60					~40-63% (5 x10^3 µg/L) / 0.7469	
			2.03		18.34		5		94%	
[85]	**CuO NPs** Copper(II) oxide nanoparticles	Double distilled water	2-10	25-45	0.4-5	0-3.0	10-150	Cr(VI)	96.3% (10 x10^3 µg/L) 86.25 (400 mg/L)	Mono elemental
			2, 3 4, 5, 6, 7, 8, 9, 10	r.t.	1.0	3.0	20		33.05-65.5% (pH 3) 13.1 (pH 3)	
			3	r.t.	0.40, 0.80; 1.2, 1.6, 2.0, 3.0, 4.0, 5.0		20		34.5-92.8% (5000 mg/L) 18.56-86.25 (400 mg/L)	
			3	r.t.	1.6	0-3.0	20		~82% (1h)	
			3	r.t.	1.6	3.0	10, 20, 30, 50, 70, 100, 150		16.33-96.3% (10 x10^3 µg/L)	
			3	25	1.6	3.0	20		83% / 15.625	
				35					17.636	
				45					94% / 18.518	
[72]	**IONPs** Magnetic iron oxide nanoparticles **MIONPs** EDTA-modified magnetic iron oxide nanoparticles		2	r.t.	0.0050-0.030	0-18	200-1000	Cr(VI)	99.90% / 499.5 (30 mg/L, MIONPs) 34.06% / 170.33 (30 mg/L, IONPs)	Mono elemental
			2	r.t.	0.0050, 0.010, 0.015, 0.020, 0.025, 0.030	3.0			320.17-499.5 (30 mg/L) MIONPs 86.88-170.33 (30 mg/L) IONPs	

						18			64.03% (5 mg/L), 77.67% (10 mg/L), 89.16% (15 mg/L), 93.77% (20 mg/L), 96.65% (25 mg/L), 99.90% (30 mg/L) MIONPs 17.37% (5 mg/L),19.15% (10 mg/L), 22.41% (15 mg/L), 25% (20 mg/L), 29.05% (25 mg/L), 34.06% (30 mg/L) IONPs	
			2	25	0.010	0.33, 0.66, 1.0, 1.3, 1.7, 2.0, 2.3, 2.7, 3.0, 18	1000		163.97 (3h), 452.26 (18h) MIONPs 147.95 (3h), 170.33 (18h) IONPs	
			2	25		3.0	200, 400, 600, 800, 1000		82.80-367.67 MIONPs (1000 x10^3 µg/L) 37.55-106.33 IONPs (1000 x10^3 µg/L)	
[68]	**Ti-AX** Titanium dioxide nanoparticles precipitated in anion exchange resins	Synthetic groundwater	8	Information not mentioned	0.60	168	0.10	Cr(VI)	88%	Multi elemental
[86]	**Cs-g-PBA/SG** Chitosan-g-poly(butylacrylate)/ silica gel nanocomposite		3-9	r.t.	10-60	1.0-6.0	62.5-1000	Cr(VI)	98% (62.5-125 x10^3 µg/L) 55.71	Mono elemental
			3, 4, 5, 6, 7, 8, 9		10	1.0	100		~94.1-97.4% (pH 7)	
					10, 20, 30, 40, 50, 60				~97.4-97.73% (60 000 mg/L)	
			7	25	10	1.0-6.0	100		~96.7-98 (5-6h)	
			7	r.t.	10	1.0	62.5, 125, 250, 500, 750, 1000		54-98% (62.5-125 x10^3 µg/L) 55.71	
[87]	**Chitosan–Fe_3O_4 nanocomposite strip** Chitosan–magnetite nanocomposite strip	Deionised water	Information not mentioned	Information not mentioned	1 cm x 1 cm 0.010 L	0.17, 0.30, 0.83, 1.2, 1.5, 1.8, 2.2	260	Cr(VI)	~15-92.33%	Mono elemental

[47]	**TF-SCMNPs** Thiol-functionalized mesoporous silica-coated magnetite nanoparticles (**Fe_3O_4 NPs**)	Distilled water	3-10	r.t. (25)	0.080-0.40	0.083-24	8	Cr(III)	42% (pH 10, 400 mg/L) 1.119	Mono elemental
			3, 5, 7, 10	r.t.	0.40	0.083, 0.17, 0.25, 0.33	8		2.5-42% (pH 10, 0.33 h)	
			10		0.080, 0.16, 0.24, 0.32, 0.40	0.33	8		1.375-42% (400 mg/L)	
			10		0.40 TF-SCMNP 0.40 Fe_3O_4	0.33	8		42% 13.875%	
			10		0.080-0.40	24	8		1.119	
[43]	**Fe-Cu binary oxide NPS**	Milli-Q water	1-9	r.t. (25)	0.10-2.5	1.0	1-25	Cr(VI)	~100% (100 mg/L, 1 x10^3 µg/L) 71.43	Mono elemental
			3	25	0.10 0.50	1.0	1, 5, 10, 25		~10-50% (1 x10^3 µg/L) 81.3% (1 x10^3 µg/L) 76.54% (5 x10^3 µg/L) 71.43% (10 x10^3 µg/L) 73.76% (25 x10^3 µg/L)	
					1.0 2.5				~92-98% (1 x10^3 µg/L) ~99-100% (1 x10^3 µg/L)	
			3	25	0.10, 0.50, 1.0, 2.5	1.0	5		27.9% (100 mg/L), 76.54% (500 mg/L), 97.48% (1000 mg/L), 99.86% (2000 mg/L)	
			1, 3, 5, 7, 9	25	0.50	1.0	5		41.25% (pH 1), 76.54% (pH 3), 71.5% (pH 5), 53.28% (pH 7), 26.82% (pH 9)	
			3	25	0.10	0-10	1.15		~40% (4 h)	
			3	25	1.0				71.43	

[51]	**MIN** Magnetic iron oxide nanoparticles **MIN-TW** Magnetic iron oxide nanoparticles/tea waste composite **MIN-SB** Magnetic iron oxide nanoparticles/sugarcane bagasse composite	Deionized water	2-7	30	0.50-1.25	0.083-2.0	50-300	Cr(III)	98.27% (MIN-SB, 1h, 1125 mg/L) 518.134 ^{d} (MIN-SB, 0.75 h)	Mono elemental
	MIN MIN-TW MIN-SB		2, 3, 4, 5, 6	30	1.0	0.75	50		83.86% / 45.93 (pH 6) 78.46% / 39.23 (pH 6) 94.23% / 47.11 (pH 6)	
	MIN MIN-TW MIN-SB		6	30	1.0	0.75	50, 100, 200, 250		90.90% / 227.25 (250 x10^3 µg/L) 89.82% / 224.558 (250 x10^3 µg/L) 96.74% / 241.87 (250 x10^3 µg/L)	
	MIN MIN-TW MIN-SB		6	30	1.0	0.083-2.0	250		93.03% / 232.59 (0.92 h) 92.83% / 232.08 (1 h) 98.27% / 245.68 (1 h)	
	MIN MIN-TW MIN-SB		6	30	0.50, 0.75, 1.0, 1.125	0.92 1.0 1.0	250		93.03 % (1125 mg/L) 232.59 (500 mg/L) 92.83% (1125 mg/L) 232.08 (500 mg/L) 98.27% (1125 mg/L) 245.68 (500 mg/L)	
	MIN MIN-TW MIN-SB					0.82 0.84 0.75			502.779 ^{c} 466.773 ^{c} 518.134 ^{d}	
	MIN MIN-TW MIN-SB			30, 35, 45					323.59 (30ºC), 242.92 (35ºC), 246.89 (45ºC) 232.08 (30ºC), 241.99 (35ºC), 245.52 (45ºC) 245.06 (30ºC), 247.16 (35ºC), 248.99 (45ºC)	
	MIN MIN-TW MIN-SB	Deionized water						Cr(III)	~229-243 ~228-240 ~243-247 (depending on the type of interfering ion)	Multi elemental

[36]	**ST/Mag NPs** Spent tea-supported magnetite nanoparticles	Double-distilled water	2-8	r.t. (20)	0.10-11.0	0.033-4.0	5-300	Cr(VI)	~100% (5 x10^3 µg/L) 30.03	Mono elemental
			2, 3, 4, 5, 6, 7, 8	20	5.0	2.0	10		~65-92.8% (pH 2)	
			2	20	0.10-11.0	2.0	10		10.1-99.7% (6000 mg/L)	
			2	20	6.0	0.033-4.0	10 100		1.44 / 99.7% (1h) 13.92 / 81.8% (1h)	
			2	20	6.0	2.0	5-300		30.03 ~55-100% (5 x10^3 µg/L)	
		Synthetic saline wastewater	2	20	3.0	1.0	10	Cr(VI)	78.3-99.9% 1.09-1.39 (depending on the concentration of interfering ions)	Multi elemental
[44]	**Fe_3O_4 NPs** Magnetic magnetite nanoparticles	Double distilled water	2-10	25-45	1.0-4.0	0-24	2-100	Cr(VI)	~75% (4000 mg/L) 34.9 (45ºC)	Mono elemental
			2, 4, 6, 8, 10	25	1.0		20		10-58.4% (pH 2)	
			2	25	1.0 2.0 4.0	0-24	50		30% / 14.01 57% / 16.13 [b] ~75% / 8.70 [b]	
			2	25	2.0	0-24	25 50 100		9.90 [b] 8.85 [b] 17.24 [b]	
			2	25, 35, 45	2.0	0-24	2-100		20.2 (25ºC), 26.8 (35ºC), 34.9 (45ºC)	
[38]			3-6	25	0.25	2.0	5.2-104	Cr(III)	343 (pH 5.4, ESH@MS-60-NH_2)	Mono elemental
	ESH Electrospun hematite nanofiber		5.4	25		2.0			208	
	ESH@MS-60 Electrospun hematite nanofiber/mesoporous silica core/shell		5.4	25		2.0			178	

	ESH@MS-60-NH$_2$ Electrospun hematite nanofiber/mesoporous sílica functionalized with amine group		5.4	25		2.0			343	
[45]	**CaFe$_2$O$_4$ NPs** Calcium ferrite nanoparticles	Ultrapure deionized water	2-6	r.t.	0.0625-1.0	0.033-1.7	30-250	Cr(III)	340 (62.5 mg/L) 99% (pH 2 / 30 x10^3 µg/L)	Mono elemental
			2, 3, 4, 5, 6		1.0	0.67	50		5.80-49.50 (pH 2) 11.5-99% (pH 2)	
					1.0		30-250		29-122 (250 x10^3 µg/L) ~49-99% (30 x10^3 µg/L)	
			2		1.0	0.033-1.67	30, 50, 70, 100, 125		~30-115 (125 x10^3 µg/L)	
			2		0.0625, 0.125, 0.25, 0.50, 0.75, 1.0	0.67	50		~340 (62.5 mg/L) > 95% (1000 mg/L)	
			2		1.0	0.67	30-250		124.11	
[46]	**MnFe$_2$O$_4$ NPs** Manganese ferrite nanoparticles	Real wastewater from galvanotechnic industry	2	r.t.	0.5-6.0	0.17-24	50-250	Total Cr	334.80 (500 mg/L) 71.37% (1500 mg/L)	Multi elemental
			2		0.50, 1.0, 1.5, 2.0, 3.0, 6.0	24			34.68-334.80 (500 mg/L) ~50-71.37% (1500 mg/L)	
			2		1.5	0.17-24			~80 / ~60% (2 h)	
			2		1.5	24	50, 100, 150, 250		~10-40 (250 x10^3 µg/L) ~25-30% (50 x10^3 µg/L)	
					1.5	2.0			89.18 / 59.35%	
[70]	**Fe$_3$O$_4$ NPs** Magnetite nanoparticles	Distilled water	7	20	0.10-1.0	0.083-24	0.25	Cr(VI)	~2.4 (24 h)	Mono elemental

		Natural-like water	5-8	20	0.10-1.0	0.083-24	0.050-1.0	Cr(VI)	~100% (pH 6.5, 3 h / pH 7.0, 4 h) 4 (pH 5)	Multi elemental
			7			0.083-24	0.25		~1.1 (24 h)	
			5-8		0.10	24	0.050-1.0		1-4 (pH 5)	
			6.5 7.0 7.5		1.0	0.50-5.8	0.10		~100% (3 h) ~100% (4 h) ~95% (5 h)	
[88]	**Fe_3O_4 NPs** Magnetite nanoparticles		1.5-4.5	10-75	0.50-2.0	0-2.0	0-160	Cr(VI)	~26 (2000 mg/L)	Mono elemental
			3.5	20	2.0	0-2.0	80		~12 (2 h)	
			1.5, 2.5, 3.5, 4.5	20	2.0	0.50	80		~5.5-13.5 (pH 1.5)	
			3.5	10, 20, 45, 75	2.0	0.50	80		~9-25 (75ºC)	
			3.5	20	2.0	0.50	0, 5, 10, 20, 40, 80, 160		~3-12 (160 x10^3 µg/L)	
			3.5	20	0.50, 1.0, 2.0	0.50	80		~10.5-12 (500 mg/L) ~7.5-26 (2000 mg/L)	
[89]	**CS–CA NPs** Chitosan–citric acid nanoparticles	De-ionized water	2-6	25-45	0.50-5.0	0-2.0	10-110	Cr(VI)	94.46% (70 x10^3 µg/L) 38.51 (500 mg/L)	Mono elemental
	CS NPs Chitosan nanoparticles		4	25	2.0	0, 0.17, 0.33, 0.66, 1.0, 1.83, 2.0	25		61.75% CS-CA (1-2 h) 83.54% CS (1-2 h)	
	CS–CA NPs		2, 3, 4, 5, 6	25	3.0	1.0	50		52.89-86.83% (pH 3) ~9-14 (pH 3)	
			4	25	0.50, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5	1.0	50		38.51-83.33% (3000-3500 mg/L) 3.88-38.51 (500 mg/L)	
			3	25	3.0	1.0	10, 30, 50,70, 90, 110		53.42-94.46% (70 x10^3 µg/L) 22.4 (70 x10^3 µg/L)	

[65]	**CuO NPs** Cupric oxide nanoparticles	De-ionized double distilled water	2.0-10.0	20-60	0.25-2.5	0-5.8	5-50	Cr(VI)	98.8% 50.0 (250 mg/L)	Mono elemental
			7.0	25	1.0	0-5.8	30		~35% (2.5-5.8 h) ~8 (2.5-5.8 h)	
			7.0	25	1.0	2.5	5, 10, 15, 20, 25, 30, 35, 40, 45, 50		21.9-91.0% (5 x10^3 µg/L) 3.5-8.55 (25 x10^3 µg/L)	
			2, 3, 4, 5, 6, 6, 7, 8, 9, 10	25	1.0	2.5	25		20-73.2% (pH 4) 4-14.07 (pH 4)	
			4.0	25	0.25, 0.50, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5	2.5	25		50-80% (1250 mg/L) 7.93-50.0 (250 mg/L)	
			4.0	20, 25, 30, 35, 40, 45, 50, 55, 60	1.25	2.5	25		13.3-86.5% (40ºC) 2.5-16.63 (40ºC)	
			3.81	37.1	1.28		22.5		98.8%	
[58]	**TiO_2 NPs** Titania nanoparticles	Deionized (MilliQ) water	2.0-12.0	28	0.010-0.50	0.083-0.75	5-100	Cr(VI)	85.85 (20 x10^3 µg/L)	Mono elemental
			2, 5, 7, 9, 12						75.47 (pH 7)	
						0.083, 0.17, 0.25, 0.33, 0.50, 0.75			79.24 (0.5 h)	
					0.010, 0.050, 0.10, 0.20, 0.50				83.01 (100 mg/L)	
			7.0		0.10	0.50	5, 10, 20, 50, 100		85.85 (20 x10^3 µg/L)	
[56]	**BnM** Biogenic nano-magnetite	Ultrapure water	12	20	0.75 Anoxic	0-350	Model solution	Cr(VI)	32	Mono elemental
		Contaminated groundwater	11.9	20	0.66 Anoxic 0.66 Oxic	0-200	16.69	Cr(VI)	24 7	Multi elemental

[48]	**PAA@VTES@Fe_3O_4 NPs** Magnetite nanoparticles coated with silane coupling agent (VTES) grafted with polyacrylic acid (PAA)	Ultrapure water	2-6	20-40	1.0-6.5	0-24	170	Cr(III)	92.5% (pH 6, 5000-6500 mg/L) 80.6 (40ºC)	Mono elemental
			2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6	30	5.0	4.0	170		56.2-92.5% (pH 6)	
			6	30	1.0, 2.0, 3.5, 4.0, 5.0, 5.5, 6.0, 6.25, 6.5	4.0	170		66.5-92.5% (5000-6500 mg/L)	
			6	20, 30, 40	5.0	0-24	170		54.1 (20ºC), 61.4 (30ºC), 80.6 (40ºC)	
				30						
		Tannery effluent	6		5.0	4.0	170	Total Cr	94.0%	Multi elemental
[64]	**Fe_3O_4 NPs** Magnetite nanoparticles	Deaerated deionized water	2-10	25-45	1.0-5.0	0-3.0	0-120	Cr(VI)	100% (pH 2, 4000 mg/L, 20 x10^3 µg/L, 40ºC)	Mono elemental
			2, 3, 4, 6, 8, 10			0-3.0			35.7-100% (pH 2)	
					1.0, 2.0, 3.0, 4.0, 5.0	0-3.0			29.1-100% (4000 mg/L)	
						0-3.0	20, 50, 70, 100		30-100% (20 x10^3 µg/L)	
				25, 30, 35, 40		0-2.0			73.8-100% (40 ºC)	
			2	40	4.0	2.0	20		100%	
							20	Cr(VI)	80-100% (depending on the type and concentration of interfering anion)	Multi elemental

[55]	**Fe_3O_4 nanospheres** Mesoporous magnetite nanospheres	Double distilled water	2-7	25-45	1.0-3.0	1.0-72	5–100	Cr(VI)	44% (1h, 2000 mg/L) 8.90 (45ºC)	Mono elemental
			2, 3, 4, 5, 6, 7	25	1.0		10		~ 27-42% (pH 2)	
			4	25	1.0, 2.0, 3.0	1.0, 48, 72	10		44% (1h, 2000 mg/L)	
			4	25	2.0		5		1.99	
							10		4.35	
							20		6.55	
			4	25, 35, 45	2.0		10		4.35 (25ºC), 4.50 (35ºC), 4.72 (45ºC)	
			4	25, 35, 45	2.0				6.64 (25ºC), 7.31 (35ºC), 8.90 (45ºC)	
		Groundwater	4	25	2.0	48	10	Cr(VI)	65%	Multi elemental
[90]	**PPY/γ-Fe_2O_3** Polypyrrole/maghemite **PANI/γ-Fe_2O_3** Polyaniline/maghemite	Deionized water	2.0-10.0	r.t.	0.2	0.083-2	2.5-100	Cr(VI)	~100% (pH 2, 2.5 mg/L) 208.8 (PPY/γ-Fe_2O_3, pH 2, 100 mg/L)	Mono elemental
	PPY/γ-Fe_2O_3		2.0-10.0			2	100		~ 48-52% (pH 2)	
	PANI/γ-Fe_2O_3								~ 33-48% (pH 2)	
	PPY/γ-Fe_2O_3		2.0			0.083-1.5	100		~52%	
	PANI/γ-Fe_2O_3								~49%	
	PPY/γ-Fe_2O_3		2.0			1	2.5, 5, 15, 25, 50, 75, 100		~ 52-100% (2.5 mg/L) 208.8 (100 mg/L)	
	PANI/γ-Fe_2O_3								~ 50-100% (2.5 mg/L) 195.7 (100 mg/L)	

[80]	**P(MMA)-g-TG-MNPs** Poly(methyl methacrylate) grafted Tragacanth gum modified Fe_3O_4 magnetic nanoparticles	Deionized water	2.0-7.0	25	3.0	0-4.2	1-30	Cr(VI)	~ 50-100% (pH 2) 7.84 (30 mg/L)	Mono elemental
			2.0-7.0						~ 50-100% (pH 2)	
			5.5	25	3.0	3.4	<20		7.64	
						0-4.2	10 20 30		3.23 6.31 7.84	
							20	Cr(VI)	91.7-98.4% (without interfering ions)	Multi elemental
		Electroplating wastewater	5.5				10-10.020	Cr(VI)	89.0-96.2% (10 mg/L)	
		Underground water	5.5				0.100-0.150	Cr(VI)	59.8-97.8% (0.100 mg/L)	
[78]	**Fe_3O_4 NPs** Magnetite nanoparticles		2-6		2.5	0.083-1.0	0.10-10	Cr(III) Cr(VI)	100% (pH 4, 0.25 h) / 0.555 100% (pH 4, 0.33 h) / 1.705 (depending on the material type)	Mono elemental
			2, 3, 4, 5, 6		2.5	1.0	0.10	Cr(III) Cr(VI)	0-100% (pH 4, depending on the material type) 50-100% (pH 4, depending on the material type)	
					2.5	0.083, 0.17, 0.25, 0.33, 0.5, 1.0	0.10	Cr(III) Cr(VI)	~10-100% (0.25 h, depending on the material type) ~70-100% (0.33 h, depending on the material type)	
			4	r.t. (21)	2.5	1.0	0.25, 0.50, 1, 5, 10	Cr(III) Cr(VI)	0.555 1.208/1.705 (depending on the material type)	
					2.5	1.0	0.10	Cr(III) Cr(VI)	~60-100% ~25-100 % (depending on the material type and on the type and concentration of interenfence anion)	Multi elemental

[77]	**Mn_3O_4** Manganese oxide nanomaterial		2-6	4-45	2.5	0.17-4.0	0.30-1000	Cr(III) Cr(VI)	90% (pH 2)/ 54.4 (45ºC) 85% (pH 2) / 5.8 (45ºC)	Mono elemental
			2, 3, 4, 5, 6	25	2.5	1.0	0.30	Cr(III) Cr(VI)	~60-90% (pH 2) ~20-85% (pH 2)	
			4	4, 26, 45	2.5	1.0	0.30, 3, 30, 300, 1000	Cr(III) Cr(VI)	~7-10 ~3	
			4	4, 21, 45	2.5	1.0	0.30-1000	Cr(III) Cr(VI)	18.7 (4ºC), 41.7 (21ºC), 54.4 (45ºC) 2.5 (4ºC), 4.3 (21ºC), 5.8 (45ºC)	
[49]	**PMMNs** Polyacrylamide modified iron oxide nanoparticles		1-8	30	20	0-2.0	50-1000	Cr(VI)	~99% (pH 3, 100 x10^3 µg/L) 35.186	Mono elemental
			1, 2, 3, 4, 5, 6, 7, 8	30	20	0.67	100		~65-97% (pH 3)	
			3	30	20	0-2.0	100		~99%	
			3	30			50-1000		64.20-98.30% (50 x10^3 µg/L) 35.186	
			3	30		0.67	100	Cr(VI)	~94-98% (depending on the type and concentration of salt)	Multi elemental
[71]	**Fe_3O_4 NPs** Iron oxide magnetic nanoparticles	Artificial wastewater	3-9	25	250-1500 mg (volume not mentioned)	0.25-1.5	250-1000	Cr(III)	99.9% (pH 9)	Mono elemental
			3, 5.5, 7.5, 9	25	1000 mg	1.0	500		32.7-99.9% (pH 9)	
			5.5		250, 500, 750, 1000, 1500 mg		500		56.9-98.5% (1500 mg)	
			5.5	25	750 mg	0.25, 0.42, 0.50, 0.75, 1.0, 1.5	500		71.2-88.7% (1.5 h)	
			5.5	15, 20, 25, 30	750 mg	0.75	500		70.7-92.9% (30 ºC)	
			6	25	1000 mg	0.75	250, 500, 750, 1000		96.96-99.1% (250 x10^3 µg/L)	

[59]	**NiO NPs** Mesoporous nickel oxide nanoparticles	Distilled water	4.7-9	30	1.0-7.0	0-0.83	10-50	Cr(VI)	~100% (10 x10^3 µg/L, 7000 mg/L) / ~5 (50 x10^3 µg/L)	Mono elemental
			4.7	30	6.0		10, 20, 30, 40, 50, 60		~40-100% (10 x10^3 µg/L) ~0-5 (50 x10^3 µg/L)	
			4.7	30	1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0		20		~20-100% (7000 mg/L) ~3-4.5 (2000 mg/L)	
			4.7, 7, 9	30	6.0		20		~94-98% (4.7)	
			4.7	30	6.0		20		4.73	
[75]	**Cr(VI)-imprinted poly(HEMAH) NPs** Chromium(VI)-imprinted hydroxyethylmethacrylate (HEMA) polymeric nanoparticles	Milli-Q ultrapure water	2-6	25	Information not mentioned	0-2	1000 -11 000	Cr(VI)	3830.58	Mono elemental
			2, 3, 4, 5, 6	25			7000		~1700-3830.58 (pH 4)	
			4	25		0, 0.33, 0.66, 1.0, 2.0	7000		3830.58 (1-2 h)	
			4	25			1000, 2000, 3000, 4000, 5000, 6000, 7000, 9000, 11 000		0-3830.58 (7000 x10^3 µg/L)	
			4	25			7000		3830.58	
[73]	**TiO_2 NPs** Titania nanoparticles		4.0	25	0.10	0-2.5	0-80	Cr(VI)	21.92	Mono elemental
			4.0	25	0.10	2.0	0-80		~13.5-21.76 (16.83 x10^3 µg/L)	
			4.0	25		0.67			21.92	
[50]	**Fe_3O_4-loaded seeds** Magnetite nanoparticles loaded natural seeds sabja		2	Information not mentioned	1000 mg (volume not mentioned)	0, 0.25, 0.50, 0.75, 1.0, 1.5, 2.0	1	Cr(VI)	~100%	Mono elemental
							5		97%	
							20		~85%	
							30		~80%	
							50		~75%	
							50	Cr(VI)	80%	Multi elemental
[91]	**Fe_3O_4/CNT NPs** Carbon nanotubes loaded with magnetite nanoparticles		2-12	20-80	1.0	0.083-120	100-1000	Cr(VI)	95% (pH 2) / 60 (pH 2)	Mono elemental
			2, 4, 6, 8, 10, 12		1.0		100		~75-95% (pH 2) 50-60 (pH 2)	
			6	20, 40, 60, 80			100-800		47.98-83.54 (80 ºC)	

[69]	**Fe_3O_4 NPs** Iron(II/III) oxide or magnetite or ferrite nanoparticles **$MnFe_2O_4$ NPs** Magnanese(II) iron (III) oxide or jacobsite or manganese ferrite nanoparticles		2-10	4-50	2.5	1.0	0.30-100	Cr(III) Cr(VI)	100% (Fe_3O_4, pH 6/7) 10.638 100% ($MnFe_2O_4$, pH 2/3) 3.455	Mono elemental
			2, 3, 4, 5, 6, 7, 8, 9, 10		2.5	1.0	0.30	Cr(III) Cr(VI)	~0-100% Fe_3O_4 (pH 6/7) ~0-80% $MnFe_2O_4$ (pH 6) ~0-60% Fe_3O_4 (pH 3/4) ~0-100% $MnFe_2O_4$ (pH 2/3)	
			6 3	23	2.5	1.0	0.30, 1, 5, 10, 25, 50, 100	Cr(III) Cr(VI)	10.638 Fe_3O_4 7.189 $MnFe_2O_4$ 3.455 Fe_3O_4 3.211 $MnFe_2O_4$	
[60]	**Magnetic PS-EDTA resin** Magnetic chelating resin with EDTA functionality		2-12	30	0.20-2.0	0.083-10	5-1000	Cr(VI)	100 % (pH 4, 10 h, 1000 mg/L, 5-40 x10^3 µg/L) 250.00	Mono elemental
			2, 4, 6, 8, 10, 12	30	1.0	6.0	30		30-100% (pH 4)	
			4	30	1.0	0.083-10	30		~100% (10 h)	
			4	30	1.0	10	5-1000		0-240.23 (1000 x10^3 µg/L) ~25-100% (5-40 x10^3 µg/L)	
			4	30	0.20, 0.60, 1.0, 1.4, 1.8, 2.0	10	30		~91-100% (1000 mg/L)	
			4						250.00	
[61]	Semicarbazone derivatives of calix[4]arene immobilized onto magnetic nanoparticles (Fe_3O_4): **MN-C1**, **MN-C2**, **MN-C3**	Deionized water	1.5-4.5	30	2.5	1.0	5.2-20.8	Cr(VI)	90% (MN-C2, pH 1.5)	Mono elemental
			1.5, 2.5, 3.5, 4.5						~30-70% MN-C1 (pH 1.5) ~70-90% MN-C2 (pH 1.5) ~60-80% MN-C3 (pH 1.5)	
			2.5	30	2.5	1.0	5.2, 10.4, 15.6, 20.8		~48-82% MN-C2 (5.2 x10^3 µg/L)	

[74]	**NC** Nanoporous carbon **Ni-NC** Nickel oxide onto nanoporous carbon **Fe-NC** Iron oxide onto nanoporous carbon	Ultrapure water	2-10	20, 30, 40	0.20	0-6.0	10-100	Cr(VI)	60.8 (Fe-NC, r.t.)	Mono elemental
			2, 3, 4, 5, 6, 7, 8, 9, 10	30	0.20		100		~20.8 NC (pH 5) ~46.8 Ni-NC (pH 4) ~52.0 Fe-NC (pH 4)	
				r.t.	0.20	6.0			~15.6 NC 44.7 Ni-NC 60.8 Fe-NC	
[92,93]	**NH_2-NMPs** Amino-functionalized nano-Fe_3O_4 magnetic polymer adsorbents	Ultrapure water	2.0-9.0	25-65	1.25	0-90	50-1000	Cr(VI)	99.9% (TEPA-NMPs, pH 2.0, 50 mg/L) 370.37 (TEPA-NMPs, pH 2.0, 35ºC)	Mono elemental
	TEPA-NMPs		2.0-9.0		1.25	24	50 500 1000		16.5-99.9% (pH 2.0) 11.5-73.9% (pH 2.0) 9.4-47.2% (pH 2.0)	
	EDA-NMPs DETA-NMPs TETA-NMPs TEPA-NMPs		2.0-9.0		1.25	24	50		>99.9% (pH 2.5) >99.9% (pH 2.5) >99.9% (pH 2.5) >99.9% (pH 2.0)	
	EDA-NMPs DETA-NMPs TETA-NMPs TEPA-NMPs		2.5 2.5 2.5 2.0	35	1.25	0-90	50		37.49 37.79 38.47 39.96	
	EDA-NMPs DETA-NMPs TETA-NMPs TEPA-NMPs		2.5 2.5 2.5 2.0	25-65	1.25		50-1000		136.98 (35ºC) 149.25 (35ºC) 204.08 (35ºC) 370.37 (35ºC)	
	EDA-NMPs		2.0-4.0	35	1.25	12	200, 400, 1000	Cr(VI)	34.19-76.70% (pH 3.5, 200 mg/L) 98.79-200.18 (pH 2.0, 1000 mg/L)	Multi elemental
	DETA-NMPs								24.96-57.85% (pH 3.5, 200 mg/L) 82.67-139.87 (pH 4.0, 1000 mg/L)	
	TETA-NMPs								45.24-81.90% (pH 3.5, 200 mg/L) 120.63-201.74 (pH 2.5, 1000 mg/L)	
	TEPA-NMPs								48.75-92.04% (pH 2.0, 1000 mg/L) 125.83-368.13 (pH 2.0, 1000 mg/L)	

[66]	**PEI-γ-Fe_2O_3@Fe_3O_4 NPs** Polyethylenimine-modified magnetic nanoparticles		2-9	15-35	4.0	0-2.0	50-500	Cr(VI)	98.2% (100 x10^3 μg/L) 83.33 (15ºC)	Mono elemental
			2, 3, 4, 5, 6, 7, 8, 9	25	4.0	0.50	100		~98-55 % (pH 2)	
			2.2	25	4.0	0-2.0	100 200 400 500		98.2% 92.6% 72.5% 64.6%	
				15, 25, 35			50-500		83.33 (15ºC), 78.13 (25ºC), 74.07 (35ºC)	
			2.2	25	4.0	0.50	100	Cr(VI)	~98-100%	Multi elemental
		Wastewater			2.67	0.50	37.98	Cr(VI)	99.0%	
[94]	**GMDFe** Nanosized ferric oxide loaded glycidyl methacrylatebased polymer		2-10	r.t. (25)	4.0	Equilibrium time	30	Cr(VI)	98% (24 h) 163.47 (pH 2)	Mono elemental
			2, 4, 6, 8, 10	25	4.0		30		163.47 (pH 2), 157.52 (pH 4), 94.38 (pH 6), 77.94 (pH 8), 27.37 (pH 10)	
			4	25	4.0	0-24	30		0-98% (24 h)	
			4	25	1000 mg (volume not mentioned)		30		138.84	
[95]	**CeO_2 NPs** Monodisperse ceria nanospheres	Simulated wastewater	Information not mentioned	r.t.	1.0	0-2.0	4.8 8	Cr(VI)	94.5% / ~4.5 94.1% / 7.52	Mono elemental
[96]	**Fe_3O_4/BC nanocomposites** Magnetite/bacterial cellulose nanocomposites	Deionized water	Information not mentioned	25	2.5	2	0, 20, 40, 60, 80, 100, 150, 200	Cr(III)	~25-70% (20 mg/L) ~0-20 (200 mg/L)	Mono elemental

[57]	**magMCM-41** Magnetic MCM-41 nanosorbents	Deionized, distilled water	2-7	r.t. (25)	1.0	Information not mentioned	106-156	Cr(VI)	98.8 (pH 2), 83.2 (pH 5)	Mono elemental
		Deionized, distilled water	2-5					Cr(VI)	67.6	Multi elemental
			5.0				156		67.6	
		Tap water	5.2				114	Cr(VI)	46.8	
		Mountain stream water	5.4				122	Cr(VI)	31.2	
			2, 5, 8						97% (pH 2), 97% (pH 5), 86% (pH 8)	
		River water	5.5				106	Cr(VI)	41.6	
[97]	**BHCB-MN** 5,11,17,23-tetra-tert-butyl-25,27-di(benzhydrazidylmethoxy)-26,28-dihydroxy-calix[4]arene immobilized silica-based magnetic nanoparticles	Deionized water	1.5	25	2.5	1	5.2	Cr(VI)	66%	Mono elemental
			2.5						~64%	
			3.5						11%	
			4.5						~0%	
[62]	**$Cu_2CO_3(OH)_2$ NPs** Malachite nanoparticles	Milli-Q water	4-9	10-40	5.0-20	1-16	20-500	Cr(VI)	82.2 75% (pH 5, 50 x10^3 µg/L)	Mono elemental
			4, 5, 6, 7, 8, 9		5.0		100		~2-15 (pH 4)	
			5	30	5.0, 10, 15, 20		100		~4-15 (20 000 mg/L)	
			5	30	5.0	1-16	20, 100, 200, 500		82.2	
				10-40			100		11.4-15.6 (40ºC)	
			5				50		75%	
			5				50	Cr(VI)	70%	Multi elemental

[63]	**NHTO** Nanoparticles of hydrous titanium(IV) oxide	Distilled water	2.0	30	1000-3000 mg (packed column)	0.013-0.026	8.0-32.0	Cr(VI)	12.94 [e] (32.0 x10^3 µg/L)	Mono elemental
			2.0	30	1000 2000 3000	0.013 0.026 0.039	16.0		10.13 [e] 11.75 [e] 12.53 [e]	
			2.0	30	2000	0.026	8.0 16.0 32.0		7.31 [e] 11.75 [e] 12.94 [e]	
		Industrial effluent wastewater	2.06	30	4000	0.026	15.67	Cr(VI)	~100%	Multi elemental
[98]	**α-Fe_2O_3 NPs** Hematite nanoparticles	Dilute simulated landfill leachate	3-8	20-35	0.50-3.0	0-24	20-200	Cr(VI)	~90% (pH 3)	Mono elemental
					1.0	0-24	20		86.5%	
							50		77.0%	
						5.0	100		69.3%	
							200		57.0%	
			3.0, 4.0, 5.0, 6.0, 7.0, 8.0						~20-90% (pH 3)	
			6.7	20	0.50, 1.0, 2.0, 3.0	0-24	20		57.2% (500 mg/L), 63.5% (1000 mg/L), 82.5% (2000 mg/L), 88.0% (3000 mg/L)	
			6.7				20	Cr(VI)	~50%	Multi elemental
[76]	**Fe_3O_4-γ-Fe2O3 NPs** Magnetite-maghemite nanoparticles	De-ionized water	2-14	r.t.	0.40	0.17-4	1-2	Cr(VI)	96% (pH 2, 1 x10^3 µg/L) 4.45 (pH 2, 2 x10^3 µg/L)	Mono elemental
			2-14	r.t.	0.40	24	1 2		0-96% (pH 2) / 0-2.4 (pH 2) 0-85% (pH 2) / 0-4.45 (pH 2)	
			3		0.40	0.17-4	1 2		70-92% (2 h) 60-85% (2 h)	
			4		0.40			Cr(VI)	35-90%	Multi elemental

[99]	**Ch-(Cu^0)** Zero-valent copper-chitosan nanocomposites	Deionized water	2.85 4.85	25	2	24	50	Cr(VI)	95.58% 94.2%	Mono elemental
[100]	Magnetic NPs:	Milli-Q water	2.0-9.3	22.5	5.0	0-1.0	20-100	Cr(VI)	100% ($MnFe_2O_4$, 0.083 h)	Mono elemental
	$MnFe_2O_4$		2.0	22.5	5.0	0-1.0	100		~100% (0.083 h)	
	$MgFe_2O_4$								~85% (0.75 h)	
	$ZnFe_2O_4$								~60% (0.5 h)	
	$CuFe_2O_4$								~50% (0.33 h)	
	$NiFe_2O_4$								~30% (0.25 h)	
	$CoFe_2O_4$								~20% (1 h)	
	$MnFe_2O_4$		2-9.3		5.0				99.5% (pH 2)	
	$MgFe_2O_4$								~10-85% (pH 2)	
	$ZnFe_2O_4$								~5-60% (pH 2)	
	$CuFe_2O_4$								~5-50% (pH 2)	
	$NiFe_2O_4$								~0-30% (pH 2)	
	$CoFe_2O_4$								~0-20% (pH 2)	

[a] Nonlinear Pseudo-second-order model. [b] Pseudo-second-order model. [c] Langmuir type 4 capacity. [d] Langmuir type 1 capacity. [e] Thomas model column capacity. [f] Room temperature.

Note that,
the conditions that are shaded correspond to the best uptake capacity or removal efficiency obtained;
in general, when the type of water is not referred, the authors may have used distilled or milli-Q water;
in the column correspondent to "Cr starting specie", total chromium concentration was quantified in the works that refer it; in the other works no mention is made regarding the specie or if it is total concentration;
in the column correspondent to "Uptake capacity (mg/g) or removal efficiency (%)", when the value does not present units, it is the uptake capacity; otherwise, it is the removal efficiency;
the value presented in parentheses in the column "Uptake capacity (mg/g) or removal efficiency (%)" corresponds to the condition that gave rise to the value of uptake capacity or removal efficiency presented;
the uptake capacity values which do not presented a subscript were obtained either experimentally or by Langmuir model;
sometimes, the authors refer to experimental conditions of experiments whose results they do not present;
from column "Type of water" until "Cr starting specie", the conditions mentioned are the same for the below lines

HIGHLIGHTS

Nanomaterials are a promise for effective water contaminants treatment;

Knowledge gaps on the evaluation of works published on chromium removal from waters;

Present work presents major experimental conditions influencing removal efficiency;

Research undertaken so far and the conditions used on this topic is here compiled.