Hexavalent Chromium Removal Using Adsorption Methods: A Review of Current Trends

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Chromium (Cr) is a heavily utilized heavy metal, extensively applied across multiple industrial sectors including metallurgy, dyes, leather, and electroplating. However, these industries often release significant amounts of toxic Cr-containing wastewater into the environment without adequate treatment which causes risks to human as we as aquatic animal. Despite the abundance of published literature on chromium remediation, there remains a lack of comprehensive understanding regarding the different adsorptive material for adsorption of Cr(VI). This comprehensive review evaluates the effectiveness and suitability of different adsorptive materials, including agricultural waste, biochar, carbon nanotubes, and activated carbon, for Cr(VI) removal from water solutions. It provides an in-depth analysis of the underlying adsorption mechanisms through isotherm and kinetics studies, highlighting their potential for improving water treatment and contaminant remediation strategies. In summary, this review offers promising insights for advancing Cr(VI) removal techniques and addressing research gaps associated with their challenges.
Keywords: Adsorption, activated carbon, bio-char, carbon nanotubes, hexavalent chromium.

1. Introduction

Chromium, a metal recognized for its high toxicity and carcinogenic properties, predominantly infiltrates waterways and soil via industrial waste discharge, presenting substantial hazards to both ecosystems and human well-being (Singh et al., 2021). This Chromium (Cr), a vital industrial component, finds extensive use across various sectors including leather tanning, paint production, paper manufacturing, electroplating processes, and dye industries (Ukhurebor et al., 2021). Chromium, unable to degrade naturally, easily enters the food chain through multiple pathways and is ranked among the top 20 most hazardous chemicals due to its high toxicity. WHO sets a guideline of 0.1 mg/L as the maximum allowable level of chromium in drinking water.

The carcinogenic properties of chromium are well-documented, leading to damage to renal and respiratory organs, as well as impacting the immune system. Trivalent chromium (Cr(III)) is generally regarded as less harmful compared to hexavalent chromium (Cr(VI)), highlighting a significant difference in toxicity among the various forms of chromium. Short-term exposure to Cr(VI) levels exceeding the WHO-recommended limit of 0.05 mg/L can lead to adverse health effects, including skin irritations, stomach ulcers, and other harmful conditions. Extended exposure to Cr(VI) can lead to various health problems. This includes harm to nerve tissues, skin inflammation, kidney circulation problems, and liver injury. In extreme cases, exposure to substantially elevated levels of Cr(VI) can result in life-threatening consequences (Tagliari et al., 2004; Monga et al., 2022).

A key focus of past and ongoing studies has been the elimination of Cr(VI) from wastewater before its discharge into the environment. Various techniques have been explored to effectively remove Cr(VI) from effluent, with multiple methods being researched for their efficiency in this process. In order to prevent the dangerous consequences of Cr (VI), it is imperative that industrial effluents be disposed of safely. This calls for a high removal enforcement strategy. For reduction of Cr(VI) from contaminated water, a variety of techniques have been used, such as bioremediation, chemical precipitation, solvent extraction, coagulation and flocculation, photocatalytic degradation, membrane separation, ultrafiltration, adsorption, electrodialysis, and ion exchange, (Karimi-Maleh et al., 2021). This review examines the adsorption process for Cr(VI) removal from aqueous solutions and offers an overview of the effectiveness of different types of adsorbents in achieving efficient elimination of chromium contamination from water.

2. ADSORPTION

Adsorption technology has been extensively applied in wastewater treatment because of its notable efficiency in removing contaminants, its straightforward operational procedures, and its capability for easy regeneration, making it a preferred choice in the field (Zbair et al., 2019). During adsorption, the molecules of the substance being adsorbed tend to gather and form a layer on the surface of the adsorbing material, driven by the attractive forces between them. The degree of adsorption varies depending on the specific adsorbent, as different adsorbents possess varying degrees of affinity for the adsorbate molecules, resulting in variations in the amount of adsorption observed. Until now, researchers have been actively seeking appropriate adsorbents that possess both a high capacity for adsorption and selectivity to effectively eliminate Cr(VI) from wastewater. Their exploration has encompassed a diverse range of materials, such as carbon-based substances, nanoparticles, polymers, and biosorbents, aiming to identify optimal solutions for efficient chromium removal from aquatic environments (Pakade et al., 2019).

3. PARAMETERS AFFECTING FOR Cr (VI) ADSORPTION

During the process of adsorption, several factors significantly influence both the rate and extent of adsorption on adsorbents. The impact of contact time on adsorption relates to how the length of interaction between the adsorbent and the adsorbate affects the adsorption process, influencing the efficiency of chromium removal from solutions. At first, when the adsorbent is added to the solution containing the adsorbate, adsorption generally rises quickly as the unsaturated and highly reactive sites on the adsorbent surface are exposed, allowing for increased binding opportunities. Next, the adsorption rate progressively slows as surface sites are filled, ultimately reaching equilibrium where the adsorption rate balances the desorption rate, and no further net adsorption occurs. The initial concentration of the substance being adsorbed in the solution is highly significant, as higher concentrations typically lead to increased adsorption up to a certain point. However, once the available adsorption sites are saturated, further adsorption may reach a plateau (Kumar et al., 2022). Secondly, temperature can impact adsorption kinetics, with higher temperatures often increasing the rate of adsorption due to enhanced molecular motion and interaction between adsorbate and adsorbent. Additionally, the pH of the solution influences both the surface charge of the adsorbent and the ionization state of the adsorbed substance, thereby modifying the adsorption characteristics and affecting the overall efficiency of the process (Ding et al., 2021). The speed of agitation also has significance, as it influences the rates of mass transfer and the duration of contact between the substance being adsorbed and the adsorbent. The nature of the adsorbent itself is crucial, as different materials possess varying surface properties and functional groups that can interact differently with adsorbate molecules. Particle size of the adsorbent also matters, with smaller particles generally providing higher surface area for adsorption. Moreover, the total adsorption capacity can be affected by the presence of other ions in the solution, which might compete with the adsorbate for available binding sites on the adsorbent, thereby reducing the efficiency of adsorption (Owlad et al., 2006). Considering these factors comprehensively is essential for optimizing adsorption processes in various applications, including wastewater treatment and purification techniques.

4. ADSORPTIVE MATERIALS

There are numerous adsorbent materials available for the extraction of Cr(VI) from water solutions, each offering different properties for effectively removing chromium contamination from aqueous environments. The different agro waste materials with or without chemical treatment have been utilized as low cost locally available adsorbent by many researches. Recently, biochar and activated carbons with high adsorption efficiency are being employed to remove various heavy metals from wastewater solutions (Ani et al., 2020; Xu et al., 2022). These materials are increasingly recognized for their effectiveness in capturing and eliminating contaminants, contributing to improved water treatment processes. Magnified adsorption materials are also used by different researchers for removals of Cr (VI) from contaminated water. This study aims to explore various adsorbent materials employed for Cr(VI) removal from wastewater, each demonstrating distinct adsorption efficiencies under different conditions, as observed in recent studies, to assess their potential for effective chromium elimination.

4.1Green Adsorbent Material

Due to the worldwide emphasis on sustainable development, there has been an increasing focus on using eco-friendly adsorbents instead of conventional synthetic ones for water purification purposes. Green adsorbents, derived from recycled materials sourced from forestry, agriculture, and biology, offer promising advantages such as abundance, low cost, and environmental friendliness (Kainth et al., 2024). The term "green adsorbents" encompasses a wide range of materials with varying origins. Important attributes of efficient green adsorbents comprise high adsorption capacity, the ability for regeneration, extensive surface area, and porous characteristics. These characteristics hold particular importance when assessing the feasibility of scaling up adsorbent utilization in water and wastewater treatment facilities, transitioning from experimental settings in the laboratory to practical implementation in real-world scenarios.

Various agricultural by products, including almond shells, mango kernel, orange peel, sawdust, maize cobs, sugar cane bagasse, banana peels, coir pith, wood chips, beet pulp, maize bran, oak leaves, rice bran, bagasse fly ash, and numerous other agro-wastes, hold potential for utilization as biosorbents.. The literature highlights the successful remediation of Cr(VI) using a range of biosorbents, including peel dust of mosambi (Saha et al., 2013), coir of coconut (Shen et al., 2010),coconut husk (Verma et al., 2021), and sugarcane bagasse (Garg et al., 2007), Other effective biosorbents include mango leaves (Nag et al., 2020), rice husk (Mitra et al., 2019), shell of walnut (Banerjee et al., 2018), and peanut shell (Banerjee et al., 2017). These studies demonstrate the potential of diverse natural materials for Cr(VI) removal, offering valuable insights for future water treatment strategies.

Tannery by-product such as buffing dust of chrome tanned and vegetabe tanned leather are also being used to remove Cr(VI) from waste water (Kumar et al., 2024). Depending on the type of tanning process used, buffing dust can either be chrome-tanned buffing dust (CTBD) or vegetable-tanned buffing dust (VTBD). Both types of buffing dust have distinct physicochemical properties that can be harnessed for environmental remediation, particularly in removing heavy metals. The use of buffing dust to adsorb Cr(VI) from effluent offers a sustainable approach to environmental remediation by simultaneously addressing two significant issues: solid waste management and effluent treatment in the leather industry. Chrome-tanned buffing dust (CTBD) removes Cr(VI) through adsorption, achieving an adsorption capacity of 11.33 mg/g (Kumar et al., 2023). Meanwhile, vegetable-tanned buffing dust (VTBD), rich in tannins and lignin, binds Cr(VI) through adsorption and complexation, with a capacity of 14.14 mg/g. This approach not only mitigates environmental pollution but also adds value to tannery waste, reducing disposal issues. By integrating waste management with effluent treatment, buffing dust serves as a cost-effective adsorbent, promoting sustainable industrial practices.

4.2 Activated Carbon

Activated carbon (AC) is a carbon-dense material obtained from organic sources like almond shells, various agricultural byproducts, and other raw materials (Ani et al., 2020). Its unique adsorption properties make it highly effective in removing contaminants from different environments. It comes in different shapes and sizes, including granules, powder, and pellets. Activated carbons possess a range of pores—micro, meso, and macropores—and feature diverse surface functional groups within their structure. Activated carbons are heavily employed in a multitude of industrial sectors due to their versatility and effectiveness. These industries include wastewater treatment, where activated carbons are employed to eliminate pollutants and contaminants from effluent streams, helping to meet environmental standards and regulations. This application is vital for reducing harmful substances in industrial discharges. Extensive studies have been carried out on the removal of Cr(VI) from aqueous solutions using activated carbon sourced from various materials. This review focuses on recent research efforts related to Cr(VI) removal via activated carbon, highlighting its adsorption capacity. A summary of relevant data is presented in Table No-1, showcasing the effectiveness of different activated carbon types for Cr(VI) adsorption. This compilation provides insights into the current state of research and potential applications for water treatment using activated carbon.

Table: 1 Adsorption of Cr(VI) from aqueous phase by activated carbon prepared by agro waste

Raw material/ agro waste	**Chemical agent for activation**	**Operating parameters for adsorption**	**Adsorption Capacity (mg/g)**	**Adsorption Isotherm and Kinetics of adsorption**	**References**
Peganum harmala seeds	H_3PO_4	Contact time- 30 min, dose-10 g/L, pH-3.0, rpm-200 rpm, temperature-25 °C,	16.66	Freundlich isotherm, Pseudo second-order	(Nasseh et al.,2021)
Eucalyptus camaldulensis sawdust	H_3PO_4	Dose-.05 g/L, pH-3.0,running time- 120 min, temp.-30 °C, rpm-220 rpm	125	Langmuir Pseudo second-order	(Haroon et al., 2020)
Paper sludge	HNO_3	pH-5.25,contact time-180 min,dose-1g/L, temperature-25 °C, rpm-150	54.45	Langmuir , Pseudo second-order	(Guan et al., 2020)
Sugar beet bagasse	H_3PO_4	Contact time- 180 min, pH-4.05, dose-1.49 g/L, rpm-150 temp.-25 °C,	52.87	Langmuir , Pseudo second-order	(Ghorbani et al., 2020)
Leather industry waste	KOH	rpm-150, pH-4.05, contact time- 180 min, temp.-25 °C, Dose-1.49 g/L	41.6	Langmuir and Temkin, Pseudo second-order	(Jimenez-Paz et al.,2023)
Rice husk	$ZnCl_2$	pH-3,running time- 90 min, tem.-25 °C, Dose-2 g/L	56.82	Freundlich isotherm	(Zhang et al.,2023)
Chestnut oak shells	H_3PO_4	pH-2.0,contact time-180 min,dose-7g/l, temp.-30 °C, rpm-150 rpm	33.0	Langmuir, Pseudo second-order	(Niazi et al., 2018)
Sunflower seed hull	$ZnCl_2$	Dose-1.0 g/L, ,pH-2.5, temp.-25 °C, Contact time- 300 min	162.6	Langmuir, Pseudo-second-order	(Zou et al., 2015)
Wood apple shell	H_2SO_4	Temp. -300 K dose-1.25 g/L, pH-1.8, equlinrium time- 100 min	151.51	Langmuir, Pseudo second-order	(Doke and Khan 2017)
Peanut shell	KOH	Temp-313 K, pH-2.0, time- 24 h, dose-0.1 g/40 mL, rpm-200	14.31	Langmuir isotherm, Pseudo-second-order	(AL-Othman et al., 2012)
Fox nutshell	$ZnCl_2$	pH-2.0,contact time 180 min,dose-0.05g/100 ml, temp-30 °C	46.21	Langmuir isotherm, Pseudo second-order kinetics	(Kumar and Jena 2017)

Rice straw and Sewage Sludge	$ZnCl_2$	Dose-2.0 g/l, contact time- 24 h, pH-2.0, temp.- 40 °C, rpm-150	138.69	Langmuir-Freundlich isotherm, Pseudo-second-order kinetics	(Fan et al .,2019)
Prosopis juliflora bark	H_2SO_4	Contact time- 90 min, pH-6.0, dose-0.1g/l, temp.-343 K	96.4	Langmuir model, Pseudo secondorder	(Kumar and Tamilarasan 2017)
Apple peels	H_3PO_4	Temp.-40 °C Dose-0.15 g/L, contact time-300 min, pH-2.2	34.59	Freundlich isotherm, Pseudo-second-order	(Enniya et al., 2018)
Phanera vahlii fruit	H_3PO_4	pH-2.0, dose-1.5 g/L, temp.-303 K, rpm-100, time- 180 min	244.1	Freundlich, Pseudo-second-order	(Ajmani et al., 2019)
Date Press Cake	NaOH	Contact time- 180 min, dose-1.5g/l, temp-25°C, pH-2.0	282.8	Redlich-Peterson, Elovich	(Norouzi et al., 2018)

Nasseh et al. (2021) proposed using powdered activated carbon (PAC) derived from Peganum harmala seeds, activated by ultrasonic waves, to effectively remove toxic chromium (Cr(VI)) from industrial tanning wastewater. This approach offers an innovative method for treating hazardous wastewater contaminants. The PAC exhibited high adsorption performance, achieving a removal efficiency of more than 99% for a Cr(VI) concentration of 20 mg/L under certain conditions. Characterization confirmed PAC's desirable properties. The study revealed a complex adsorption mechanism and emphasized PAC's effectiveness as a treatment agent for Cr(VI)-contaminated wastewater.

Haroon et al. (2020) developed chemical activated carbon (AC) using Eucalyptus camaldulensis sawdust (ECS) to treat hazardous Cr (VI) from contaminated water. The raw sawdust was carbonized in two stages and activated with H3PO4.The prepared activated carbon was showing over 80% removal of Cr (VI). The activated carbon, named AC-ECS, was further studied in batch and column reactors. Various factors such as contact time, pH, temperature, initial Cr(VI)concentration, size of adsorbent, and bed height of column were adjusted to optimize the process. AC-ECS showed adsorption that depended on pH, with the highest efficiency observed at pH 3.0, demonstrating its optimal operating conditions. The adsorption process was best explained by the Langmuir isotherm and pseudo-second-order kinetics, suggesting a maximum theoretical capacity of 125 mg g−1. This indicates the formation of a monolayer of adsorbate on the adsorbent surface and a rate-limiting step in adsorption. Column experiments exhibited enhanced breakthrough curve durations as the bed height increased, aligning well with the bed depth service time model. The findings suggest that up scaling AC-ECS treatment could effectively manage freshwater contamination with Cr (VI).

Guan et al. (2020) investigated the production and performance of activated carbon made from paper sludge for removing small quantities of Cr(VI) from wastewater. The paper sludge-derived activated carbon (psAC) demonstrated a significant removal efficiency of 54.04 mg/g, showcasing its potential as an effective adsorbent. The research, conducted using batch tests and characterization techniques such as kinetics, isotherms, and thermodynamics, revealed that the removal of Cr(VI) by psAC was driven by chemisorption. This process was particularly influenced by hydrogen bonding, especially in acidic conditions, highlighting the significant role of chemical interactions in Cr(VI) elimination. Additionally, the Cr(VI)-laden psAC demonstrated satisfactory catalytic performance in furfural hydrogenation. This research indicates optimistic possibilities for devising technically and economically viable approaches for treating industrial wastewater containing low concentrations of Cr(VI), all while effectively handling the disposal of paper sludge.

Zang et al. (2023) conducted a study on rice husk-based activated carbon (RHAC) prepared using zinc chloride. They characterized RHAC's pore properties and chemical attributes using various techniques including BET surface area, XRD, and FTIR. The activated carbon exhibited an impressive specific surface area of 1719.32 m^2/g and a total pore volume of 1.05 cm^3/g. Its effectiveness in removing Cr(VI) from water was evaluated by analyzing several factors, including contact time, pH, amount of adsorbent, initial chromium concentration, and temperature. These variables were thoroughly examined to understand their impact on the removal efficiency and optimize the conditions for maximum adsorption performance. The ideal pH for Cr(VI) removal was determined to be between 2.0 and 3.0, with the equilibrium reached after 90 minutes. The highest adsorption capacity of 56.82 mg/g was observed at pH 3.0, indicating optimal conditions for efficient Cr(VI) removal. Different kinetic and isothermal models were used to analyze the adsorption process and its duration. Simulation of the model indicated that external mass transfer played a key role in determining the rate at which Cr(VI) was absorbed onto the adsorbent.

Niazi et al. (2018) conducted adsorption experiments utilizing activated carbon produced from chestnut oak shells. The resulting activated carbon demonstrated a strong adsorption capacity for Cr(VI) removal from water solutions, showcasing its potential as an effective and sustainable material for treating chromium-contaminated water. The activated carbon was synthesized through chemical activation with H3PO4, followed by carbonization at 450°C, achieving a surface area of 989.4 m^2/g. FTIR analysis revealed functional groups responsible for enhancing Cr(VI) adsorption, highlighting the material's suitability for water treatment applications. At a pH of 2.0 and a contact time of 2 hours, the activated carbon achieved a maximum adsorption capacity of 33 mg/g. The Langmuir isotherm model accurately described the adsorption process, while kinetic studies indicated that chromium (VI) adsorption followed a pseudo-second-order mechanism, emphasizing chemisorption.

Doke et al. (2017) investigated the adsorption of Cr(VI) using activated carbon derived from wood apple shell. The process involved treating powdered wood apple shell with sulfuric acid (H2SO4) and then heating the mixture in a muffle furnace at 600°C for 2 hours to obtain activated carbon with a BET surface area of 1898 m^2/g. In batch tests, the highest adsorption efficiency of 95.0% was achieved under conditions of pH 1.8, an adsorbent dose of 1.25 g/L, and an initial Cr(VI) concentration of 75 mg/L. The Langmuir isotherm model best represented the adsorption process, showing a maximum monolayer adsorption capacity of 151.51 mg/g at 300 K. The dimensionless separation factor indicated that adsorption was favorable. Kinetic analysis revealed a chemisorption mechanism, following a pseudo-second-order model and involving intra-particle pore diffusion, highlighting the adsorption dynamics.

Enniya et al. (2018) synthesized activated carbon from apple peels for chromium adsorption. They treated apple peels with H3PO4 in a 2.7:1 ratio, followed by heating in a muffle furnace at 619°C for 56 minutes. FTIR analysis showed changes in peak intensity and position after Cr (VI) adsorption, particularly at 1834 cm^{-1} and 1555 cm^{-1}. SEM images revealed a porous structure resulting from H3PO4 reaction and carbonization. The activated carbon exhibited maximum chromium adsorption (34.59 mg/g) at pH 2 and increased adsorption with higher doses. The Freundlich isotherm and pseudo-second-order kinetics effectively characterized the adsorption process, with thermodynamic parameters suggesting that the adsorption was spontaneous and endothermic.

The adsorption of Cr (VI) was investigated by Fan et al. (2019) using activated carbon that was made by co-pyrolyzing rice straw and sewage sludge and activated with ZnCl2.The rice straw and sewage sludge were combined to enhance carbon content, then mixed with ZnCl2 in 1:2 ratio and heated at 600°C for 2 hours. The pH studies revealed optimal removal (97.7%) at pH 2.0 due to surface protonation at lower pH levels. Kinetic analysis showed rapid Cr (VI) removal within 0–6 hours, attributed to abundant vacant sites on absorbent material. The adsorption kinetics were most accurately described by the pseudo-second-order model (R2=0.99), revealing an adsorption capacity of 47.7 mg/g. The Langmuir-Freundlich model fitting resulted in a capacity of 138.69 mg/g at 40°C.FTIR spectra highlighted peaks corresponding to O-H,C-H vibrations, and -COOH groups before and after adsorption.

4.3 Other Adsorbent Materials

Other potential adsorptive materials include bio-char, metal oxides, zeolites, carbon nanotubes, polymer based nanomaterials and various bio-based adsorbents, each offering unique advantages for Cr(VI) removal applications. Biochar, a carbon-intensive substance produced through the pyrolysis of organic materials, has attracted considerable interest for its effectiveness in environmental cleanup, especially in adsorbing pollutants like Cr(VI) from water solutions (Xu et al., 2022). Its porous structure and high surface area make it a promising material for water treatment, offering an eco-friendly and cost-effective approach to removing contaminants. The adsorption process entails the binding of Cr(VI) ions to the biochar surface via several mechanisms, including electrostatic forces, ion exchange, and surface complex formation. These interactions enhance biochar's effectiveness in removing Cr(VI) from aqueous environments. The porous nature and extensive surface area of biochar offer numerous binding sites for Cr(VI) adsorption, making it a highly efficient and eco-friendly option for water purification (Colantoni et al., 2016). This characteristic enhances biochar's potential as a sustainable material for contaminant removal. Additionally, the surface functional groups present on biochar, such as hydroxyl and carboxyl groups, can enhance the adsorption capacity by forming strong bonds with Cr(VI) ions. Furthermore, the use of biochar as an adsorbent offers the added benefit of recycling organic waste materials, thereby reducing environmental pollution while simultaneously addressing water contamination issues. Overall, the adsorption of Cr(VI) by biochar presents a promising avenue for the remediation of chromium-contaminated water sources, contributing to both environmental sustainability and public health protection.

The use of nanomaterials for chromium removal from contaminated waters has gained significant attention due to their high surface area and enhanced adsorption capacities. Recent reviews highlight various nanomaterials, such as nanoparticles, nanotubes, and nanosheets, for efficiently removing chromium from water (Almeida et al., 2019). These materials offer promising solutions for water purification, overcoming limitations of traditional adsorbents by achieving faster removal and higher efficiency. Carbon nanotubes (CNTs) are being increasingly recognized as a promising solution for eliminating Cr(VI) from water due to their distinctive structure and excellent ability to adsorb contaminants (Jia et al., 2022). The extensive surface area and unique hollow configuration of CNTs create numerous active sites where Cr(VI) can be captured, and their tiny size helps in swiftly transferring mass. The electron-rich nature of CNTs fosters robust interactions with Cr(VI) ions, ensuring effective adsorption. Moreover, by modifying CNT surfaces with diverse functional groups, their capability to adsorb Cr(VI) can be further improved, along with selectivity for this specific contaminant. Altogether, utilizing carbon nanotubes presents a highly efficient and adaptable method for removing Cr(VI) from water, offering considerable potential in combating chromium pollution during environmental restoration endeavors (Ahmed et al.,2017).

5. CONCLUSION

This study provides clear details about chromium (Cr) in the environment, where it comes from and how it pollutes the receiving water. This study highlights the detrimental impact of chromium on living organisms and reviews various techniques for removing Cr(VI). The methods explored aim to mitigate toxicity and improve environmental and water quality management effectively. This study focused about adsorption method for removal of Cr (VI) by different adsorption materials such as agro waste from plant kingdom, carbon nanotubes and activated carbon prepared by different chemicals like H3PO4, ZnCl2 and HNO3 etc. Activated carbons have proven to be efficient and economically feasible substances with considerable potential for remediation of Cr (VI) from effluent generated by different industries. The isotherm and kinetic studies have been summarized for various types of activated carbon, elucidating the adsorption mechanism of Cr(VI).

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