ScienceDirect

Environmental Research
Volume 213, October 2022, 113723

Carbon-based adsorbents as proficient tools for the removal of heavy metals from aqueous solution: A state of art-review emphasizing recent progress and prospects

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https://doi.org/10.1016/j.envres.2022.113723
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Abstract

Carbon-centric adsorbents (CCA) are diverse forms, from simple biochar (BC) to graphene derivatives, carbon nanotubes (CNTs), and activated carbon (AC), which have been vastly explored for their removal of a plethora of pollutants, including heavy metals (HM). The prominent features of CCA are their operational attributes like extensive surface area, the occurrence of flexible surface functional groups, etc. This work offers a comprehensive examination of contemporary research on CCA for their superior metal removal aptitude and performances in simulated solutions and wastewater flows; via portraying the recent research advances as an outlook on the appliances of CACs for heavy metal adsorption for removal via distinct forms like AC, BC, Graphene oxide (GO), and CNTs. The bibliometric analysis tool was employed to highlight the number of documents, country-wise contribution, and co-occurrence mapping based on the Scopus database. The coverage of research works in this review is limited to the last 5 years (2017–2021) to highlight recent progress and prospects in using CCAs such as AC, BC, GO, and CNTs to remove HM from aqueous media, which makes the review unique. Besides an overview of the common mechanisms of CACs, the future scope of CAC, especially towards HM mitigation, is also discussed in this review. This review endorses that further efforts should be commenced to enhance the repertory of CCAs that effectively eliminate multiple targeted metals in both simulated and real wastewater.

Introduction

In recent decades, rising population, industrialization, and fast urbanization have all contributed to various forms of environmental contamination. Dumping untreated sewage (e.g., industrial effluent, residential, and commercial) directly into aquatic environments such as rivers, reservoirs, and the sea is seen as a rapid and affordable dumping technique in locations where sewage treatment plant facilities are not well established. These improper waste management practices lead to severe water contamination (Dayana Priyadharshini et al., 2021). Furthermore, the ability of large levels of dangerous pollutants to permeate human and animal food chains could pose serious health risks (Hena et al., 2021). The environment has been intensively contaminated with assorted pollutants such as organic compounds, inorganic ions, organometallic compounds, gaseous pollutants, nanoparticles, radioactive isotopes, etc. (Briffa et al., 2020). Among these, toxic and persistent heavy metals are receiving wide attention among environmental researchers because they are non-degradable or non-destroyable and accumulate in the environment, which enters to food chain over time, posing a serious environmental danger (Priyadarshanee and Das, 2021). The term “heavy metal” is to refers to metallic chemical elements and metalloids with an atomic density < 4g/cm ^{3} that are hazardous to the environment and humans (Briffa et al., 2020).

However, few heavy metals [such as copper (Cu), Nickel (Ni), Cobalt (Co), Manganese (Mn), Zinc (Zn), and Iron (Fe)] are required for the survival of living creatures because they are involved in a variety of cellular and metabolic reactions; still, they become toxic at a higher level. Many other metals and metalloids, on the other hand, are hazardous due to their toxicity, xenobiotic nature, and lack of biological function (e.g., Chromium (Cr), Cadmium (Cd), Arsenic (As), Lead (Pb), Mercury (Hg), and so on) (Anandaraj et al., 2017; Mohapatra et al., 2017; Muthukumaran et al., 2021). Unlike organic contaminants, the heavy meals do not readily degrade by a chemical or biological process; instead, they can only be transformed into reduced form with less toxicity, e.g., Cr(VI) to Cr(III), As(III) to As(V), and Hg(II) to Hg (Priyadarshanee and Das, 2021). Removal of heavy metal ions from contaminated areas achieved via various methods such as chemical precipitation, membrane filtration, ion exchange, bioaccumulation, and degradation have been developed to reduce metal bioavailability (Yang et al., 2019). However, each method has its merits and demerits (Liu et al., 2019). For instance, chemical-mediated remediation has its drawbacks, such as the involvement of chemicals, which may generate secondary waste and makes these techniques not fascinating the priority.

Hence, the adsorption of HM from aqueous solutions utilizing carbonaceous materials as adsorbents is possibly one of the most cost-effective and performance-enhanced approaches (Mehdi Sabzehmeidani et al., 2021). CCA, including AC, BC, GO, and CNTs, have been extensively researched for the mitigation of diverse HM via adsorption (Akhter et al., 2021; Duan et al., 2020). The extensive review of data on the CCA-mediated removal of HM from aqueous solution in recent years encouraged analysis of the reported findings as an essential step in escalating and systematizing the relevant knowledge to fill the attention of researchers on a global scale. Hence, in this review, the literature coverage is limited to 2017–2021 to highlight the recent progress on the use of CCA such as AC, BC, GO, and CNTs to remove HM that exists in aqueous media, as well as the attributes assigned to adsorbent and adsorbate interaction are also discussed.

Section snippets

Bibliometric analysis

A standard and successful way of identifying research trends and difficulties is bibliometric analysis. It has been applied to various scientific and engineering fields (Han et al., 2020). Because scientific journals are the primary communication route among scientists, we relied on data from the Scopus scientific database for our investigation. Scopus was chosen as a data source since it is widely regarded as one of the most comprehensive and reliable scientific databases on transdisciplinary…

Concerns about heavy metals

The continuous accretion of HM and metalloids in the natural environment has been mostly polluted by discharges from rapidly escalating industrial practices, disposal of elevated metal wastes, ore mining, domestic sewage sludge, additives of gasoline and paints, pesticides, insecticides, and prolonged use of chemical fertilizers and the use of wastewater for agricultural purposes (Priyadarshanee and Das, 2021). HM toxicity is defined as a metal's ability to harmful microorganisms, and it is…

Common mechanism for HM adsorption on CCA

Adsorption is defined as the mass transit of chemicals from a gaseous or liquid state to solid contact. It's a method in which molecules move out of solution and, as a result, get physically and chemically linked to the chemical's surface. Adsorption varies from absorption in that it is based on the surface rather than volume. The term “sorption” is used to describe both absorption and adsorption, while desorption is the reverse of adsorption (Ugwu et al., 2020). Adsorption has benefits over…

Application of CACs for HM removal

CCAs have great characteristics such as density, hardness, and strength, which makes them a superior material to chemically connect with many different types of carbon compounds through strong covalent bonds. Surface functional groups (such as carboxyl, phenyl, and lactone groups) can boost carbon surface charges to improve HM uptake (Demiral et al., 2021). Sulfuration, oxidation, and nitrogenation are the most often used procedures to improve specific pore structure, surface area, adsorption…

Future prospects

Lab-scale experiments have elucidated the vast potential of CCAs as the prime agent for heavy metal removal, but the majority will not get practical reasons under larger-scale remediation scope. Cost-consideration is an enormous concern, as most of these CCAs in the form of GO, CNTs, etc., are high-priced to generate in substantial quantities; these types (Nanoparticle-centric) are also considered now harmful to the environment and could develop as toxins/contaminants if they are not…

Conclusion

Carbon-centric adsorbents perform a pivotal part in the remediation cum mitigation of heavy metals from various systems and domains, including an aqueous environment. From a functional perspective, surface adjustment of CCA with optimizing their physicochemical and sportive attributes is vital in creating novel and unique technologies for environmental remediation. One key area of research deals with the surface modification of CCA by incorporating tailormade functional groups on the CCA…

Funding source

No funding was sourced for this review article.…

Author contribution

All the authors designed, writing, review, editing and revise the manuscript.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Acknowledgments

The authors would like to thank those who all the been instrumental in the creation of this review article.…

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