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Sawdust-based adsorbents for water treatment: An assessment of their potential and challenges in heavy metal adsorption

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A B S T R A C T

Addressing the pressing issue of heavy metal contamination in water, recent advancements in sawdust-based adsorbents present a promising, sustainable solution, as sawdust offers low cost, abundant availability, and renewability. This review examines developments from 2019 to 2024, incorporating a detailed strengths, weaknesses, opportunities, and threats (SWOT) analysis that emphasizes sawdust's strengths, such as its widespread accessibility, economic feasibility, and compatibility with circular economy goals by repurposing wood waste for water treatment. Modification techniques, including chemical treatments and nanocomposites, enhance adsorption capacity, allowing sawdust to effectively target various contaminants and adapt to different water types. Despite these strengths, challenges include pH sensitivity, composition variability, and risks of secondary pollution from certain modifications, which can complicate standardization and performance consistency. Opportunities for improvement arise through advanced modifications, such as magnetic separation, which enables easier material recovery and increases application flexibility. However, threats remain from competing technologies like activated carbon and ion exchange, and from the complexities involved in scaling up laboratory findings to industrial applications. Mechanistic studies reveal that adsorption primarily follows Langmuir and Freundlich isotherms, while kinetics often reflect pseudo-second-order behavior, indicating chemisorption as the main interaction. The analysis highlights key priorities for future research, including the development of efficient regeneration methods, enhanced stability, and field-based testing across diverse environmental conditions. Sawdust-based adsorbents thus represent a viable pathway for heavy metal removal, offering a cost-effective, renewable approach to meet urgent environmental challenges and advancing global sustainability goals.

1. Introduction

The occurrence of heavy metals (HMs) in aquatic environments is predominantly linked to anthropogenic sources, including industrial effluents from metallurgy, textiles, rubber, paper production, and pigment manufacturing, as well as agricultural runoff resulting from the application of pesticides and fertilizers (Piwowarska et al., 2024; P. Saravanan et al., 2024; Singh et al., 2024; Uddin et al., 2021). In contrast, natural inputs such as rock weathering or volcanic activity contribute relatively little (Kopittke et al., 2019; Yang et al., 2022; Zeng et al., 2020). Water pollution by HMs represents one of the most pressing environmental challenges of the 21st century, with significant implications for human health, ecosystem stability, and sustainable development (Bănăduc et al., 2022; Li et al., 2022; Zamora-Ledezma et al., 2021). HMs, including lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), and nickel (Ni), are particularly concerning due to their persistence in the environment, non-biodegradability, and tendency to bioaccumulate in living organisms (Edo et al., 2024; Priya et al., 2022; Salehi et al., 2021). These characteristics make them exceptionally hazardous, even at low concentrations, with potential to cause severe

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health issues including neurological disorders, organ damage, and various forms of cancer (Fu and Xi, 2020; Mitra et al., 2022; Sall et al., 2020).

The global acceleration of industrial development and agricultural intensification has exacerbated heavy metal contamination in water bodies, creating an urgent need for effective remediation strategies. For instance, Zamora-Ledezma et al. (2021) report that industrial discharge and mining activities have led to elevated concentrations of Pb(II) and Cd(II) in Latin American rivers. In Kumar et al. (2019) conducted a global meta-analysis showing that over 40 % of surface water samples analyzed between 2000 and 2018 surpassed permissible levels for at least one heavy metal, particularly in urban and agricultural zones.

The prevalence of HMs in drinking water varies significantly across regions, with developing countries showing particularly elevated levels due to limited water treatment infrastructure (Bijekar et al., 2022; Gallego-Schmid and Tarpani, 2019; Mukhopadhyay et al., 2022). Recent case studies demonstrate this variation: in Bangladesh's Mogla Bazar landfill area, groundwater contained Mn (0.26 mg/L), Fe (0.24 mg/L), and Pb (0.16 mg/L) exceeding World Health Organization (WHO) limits (R. Alam et al., 2020). Mukhopadhyay et al. (2022) highlight widespread contamination of rural drinking water supplies in Bangladesh and India, where arsenic (As), Pb(II), and Cr(VI) have been detected above safe thresholds in both surface and groundwater. China's Han River reservoirs showed lower but detectable Zn (0.84 mg/L) and Cu (0.46 mg/L) (Zhang et al., 2021), while Vietnam's urban waterways contained extreme Fe concentrations (2.83 mg/L), alongside Pb (2.77 μg/L) (Le and Nguyen, 2024). Similarly, Bijekar et al. (2022) identify deficiencies in wastewater treatment in sub-Saharan Africa, where untreated effluents containing Zn(II), Cu(II), and Ni(II) are often released directly into water bodies. In many such areas, chronic exposure to sub-lethal concentrations of multiple HMs occurs over extended periods, with significant public health implications including developmental toxicity and metabolic dysfunction (Kim et al., 2022; Zwolak, 2021).

These examples illustrate the global spectrum from trace contamination to hazardous levels that frequently surpass WHO guidelines in vulnerable regions (Kumar et al., 2019; Rushdi et al., 2023; Vardhan et al., 2019; Wong et al., 2022). This global variability underscores a pressing public health concern, as even low-dose, long-term exposure to HMs through drinking water can result in cumulative and often subtle health effects (Ahamed et al., 2020; Kim et al., 2022; Zwolak, 2021). Effectively addressing this issue demands a comprehensive strategy that integrates enhanced monitoring systems, context-specific regulatory measures, and the implementation of innovative treatment technologies suited to local conditions (Leburu et al., 2024; Tracy et al., 2020). Fig. 1 highlights the anthropogenic pathways by which HMs contaminate water: industrial discharges including effluents from mining, electroplating, battery manufacturing, and tanning that release high concentrations of Pb, Cd, and Cr (P. Saravanan et al., 2024); agricultural runoff carrying Cu and Zn from metal-containing fertilizers, pesticides, and animal manures (Kopittke et al., 2019); and urban wastewater and stormwater—which introduce Hg, Ni, and Zn via sewage sludge, landfill leachate, and tire-/brake-wear particles (Salehi et al., 2021). These human-derived inputs create complex metal mixtures that sawdust-based adsorbents must effectively remove in practical treatment scenarios.

Although current water treatment technologies are effective for HMs removal, each method suffers from significant limitations. Chemical precipitation, while widely used, generates toxic sludge that requires costly disposal and poses secondary contamination risks (Benalia et al., 2022; Ko, 2024). Membrane filtration is energy-intensive and prone to membrane fouling, leading to reduced efficiency and frequent membrane replacement (Xiang et al., 2022; Zhu et al., 2021). Electrochemical treatments demand high operational costs, continuous power supply, and specialized infrastructure, making them unsuitable for decentralized applications (dos Santos et al., 2021; Garcia-Segura et al., 2020). Additionally, these methods often rely on non-renewable materials and synthetic chemicals, undermining their environmental sustainability (Faheem et al., 2025; Priyanka et al., 2024). Given these constraints, there is a pressing need for alternative solutions that are not only effective but also economically viable and ecologically sound.

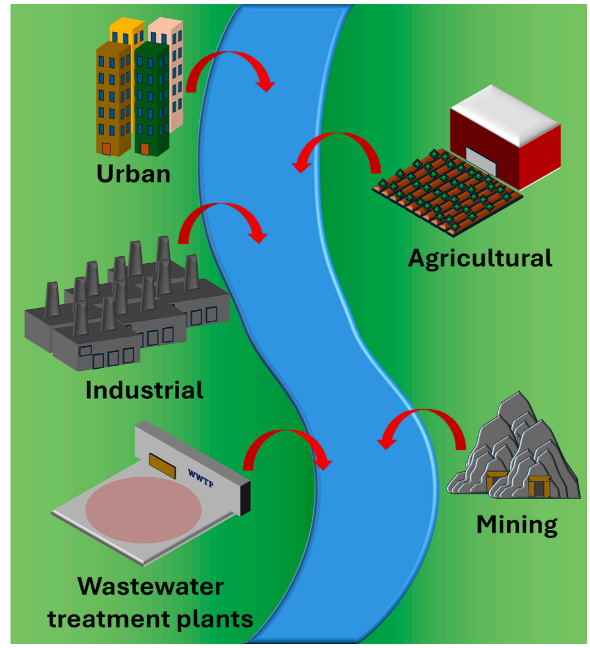

Fig. 1. Main anthropogenic and natural sources of heavy metals in aquatic environments.

Adsorption is widely recognized as an effective method for HMs removal, continuing to attract considerable attention from the scientific community (Khanzada et al., 2024; Saleh et al., 2022; Staszak and Regel-Rosocka, 2024; Wibowo et al., 2024). Recent advances in sustainable water treatment have increasingly focused on the development of eco-friendly, cost-effective adsorbents for HMs removal (Ayach et al., 2024; Bolisetty et al., 2019; Hama Aziz et al., 2023; Hussain et al., 2024). Among various options, sawdust-based adsorbents (SBA) have gained particular interest due to their unique advantages. Sawdust (SD) is a plentiful byproduct of the wood processing industry (Udokpoh and Nnaji, 2023). Its widespread availability, low cost, and inherent physical and chemical properties make it particularly suitable for adsorption applications (Raji et al., 2023). The lignocellulosic structure of SD, comprising cellulose, hemicellulose, and lignin, provides numerous functional groups capable of binding HMs ions, while its porous nature offers favorable surface area characteristics for adsorption processes (Chakhtouna et al., 2024; J. Jiang et al., 2024).

The effectiveness of SBA has been substantiated by numerous studies reporting notable adsorption capacities. For example, HCl and PANI-modified coco wood SD achieved Pb(II) adsorption capacities as high as 738.9 mg/g, one of the highest among tested materials (Tatu-Qassim et al., 2023). Likewise, phosphorylated wood SD showed high removal performance for Cd(II) and Cr(III), reaching capacities of 284.1 mg/g (Alhumaimess et al., 2019). Modified SDs such as AMPS-AA-treated fir wood SD also demonstrated excellent removal efficiencies for Pb(II), Cu (II), and Zn(II), with capacities exceeding 240 mg/g in all cases (Zhou et al., 2023). In addition to capacity, SBA demonstrate rapid kinetics, often reaching equilibrium in under 60 min, and follow pseudo-second-order models indicative of chemisorption (Chakraborty et al., 2021; Ibrahim et al., 2022; Nurnabi et al., 2020). Case studies with NaOH-treated jackfruit wood SD for Pb(II) and Fe_3O_4-modified olive wood SD for Pb(II) confirm these trends, showing high adsorption and favorable fit to the Langmuir model, which suggests monolayer adsorption (El-Sheikh et al., 2019; Mutiara et al., 2019). These findings reinforce SBA's practicality for real-world water treatment scenarios.

Fig. 2 illustrates the growing research interest in the interrelated topics of "heavy metal," "water," "adsorption," and "sawdust," showing a steady rise in publications over the past 20 years. The three distinct trends reflect an increasing scholarly focus on understanding heavy metal contamination in water and exploring adsorption-based remediation strategies, including the use of low-cost materials such as SD. The notable rise in publications involving adsorption since 2015 may suggest a growing recognition of the need for sustainable and affordable approaches to water treatment, particularly in response to increasing environmental pressures and resource limitations (Ngeno et al., 2022; W. Wang and Wang, 2022).

The growing interest in circular economy principles and sustainable resource management has further highlighted the significance of SBA (Babu et al., 2022; Nighojkar et al., 2022). By transforming a waste product into a valuable material for environmental remediation, these adsorbents exemplify the principles of waste valorization and resource efficiency (Akhtar et al., 2024; Omran and Baek, 2022). This alignment with sustainability goals, combined with their demonstrated effectiveness in HMs removal, positions SBA as a promising solution for addressing water pollution challenges while promoting environmental sustainability (Liu et al., 2023; Patro et al., 2024).

Table 1 summarizes the extensive research on SD effectiveness as an adsorbent for HMs removal, covered in numerous review articles. While these reviews have comprehensively covered the adsorption mechanisms, modification approaches, and performance of SBA, several critical aspects warrant further in-depth analysis to fully assess the potential and limitations of these adsorbents.

The objective of this review is to provide a comprehensive analysis of the recent advances in the development and application of SBA for the removal of HMs from aqueous solutions between 2019 and 2024. Unlike previous reviews that have primarily focused on the technical merits of SBA, this study adopts a strategic SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis framework to gain a holistic understanding of the practical implementation challenges and future prospects of this technology.

The SWOT analysis not only highlights the key advantages that make SD a promising and sustainable solution for water treatment, but also identifies the critical challenges that need to be addressed to facilitate the large-scale adoption of these adsorbents. This includes an evaluation of material property variability, regeneration efficiency, secondary pollution risks, and cost-effectiveness trade-offs, which are often overlooked in traditional literature reviews. Furthermore, the analysis outlines the emerging opportunities for enhancing the performance and versatility of SBA, as well as the potential threats posed by market competition, climate change impacts, and intellectual property barriers. This systematic assessment is expected to offer valuable insights to researchers, industry practitioners, and policymakers interested in

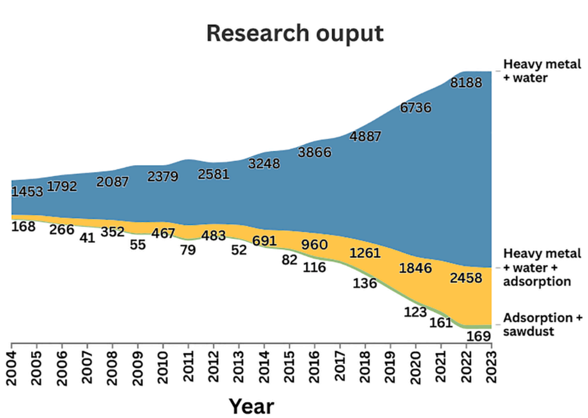

Fig. 2. Research output from Scopus over the past 20 years related to the terms "heavy metal", "water", "adsorption", and "sawdust", illustrating a growing interest.

Table 1
Summary of recent reviews on the topics of HMs removal and SBA, and contrast with present review's focus and novelty.

Review	Focus and novelty	Contrast with this review
Utilizing adsorption of wood and its derivatives as an emerging strategy for the treatment of heavy metal-contaminated wastewater (J. Jiang et al., 2024)	Overview of SD adsorbents for HMs ion removal, with emphasis on recent modifications to improve environmental adaptability.	Evaluation of SBA implementation barriers and opportunities, with analysis of modification drawbacks, including pollution risks and waste management challenges.
Sawdust, a versatile, inexpensive, readily available bio-waste: From mother earth to valuable materials for sustainable remediation technologies (Mallakpour et al., 2021)	Survey of SD applications in water treatment and material production, alongside a comparison of current modification approaches for performance enhancement.	Assessment of competing applications as threats to SD availability, with review of modification cost-effectiveness and environmental trade-offs.
Toxic heavy metal ions contamination in water and their sustainable reduction by eco-friendly methods: isotherms, thermodynamics and kinetics study (V. Singh et al., 2024)	Analysis of adsorption methods for HMs removal, complemented by a systematic review of mathematical modeling approaches in the literature.	Investigation of SBA real-world performance limitations, with analysis of discrepancies between theoretical models and practical challenges.
Sawdust-biomass based materials for sequestration of organic and inorganic pollutants and potential for engineering applications (Adegoke et al., 2022)	Comprehensive review of SBA properties for pollutant removal, with a summary of recent advances in adsorbent characterization and mechanism studies.	Evaluation of material property variability as a barrier to standardization and scale-up, with analysis of gaps between laboratory characterization and industrial performance.
Potential of sawdust materials for the removal of dyes and heavy metals: examination of isotherms and kinetics (Sahmoune and Yeddou, 2016)	Synthesis of published studies on SD as an adsorbent for dyes and HMs, with identification of knowledge gaps in regeneration and column applications.	Analysis of limitations in current research methodologies and equilibrium time determinations, with quantitative analysis of regeneration efficiency losses over multiple cycles.
Sawdust for the Removal of Heavy Metals from Water: A Review (Meez et al., 2021)	Critical assessment of literature on HMs removal using SD as adsorbent, with a systematic comparison of reported adsorption parameters and thermodynamic studies.	Evaluation of practical implementation challenges, with analysis of performance variability under real operating conditions.
Reuse of Sawdust in Developing Countries in the Light of Sustainable Development Goals (Udokpoh and Nnaji, 2023)	Overview of state-of-the-art sustainable applications of SD across industries, with analysis of current frameworks linking its use to sustainability goals.	Analysis of market competition and economic threats to sustainability goals, with evaluation of climate change impacts on the long-term sustainability of SBA solutions.
Adsorption of heavy metal ions by various low-cost adsorbents: a review (Chakraborty et al., 2022)	Systematic comparison of reported waste-based adsorbents for HMs removal, alongside a comprehensive assessment of recent advances in material modifications.	Assessment of public perception barriers to waste-based treatment adoption, with analysis of intellectual property landscapes as barriers to technology implementation.
Removal of heavy metals from wastewater using agricultural byproducts (Alalwan et al., 2020)	Assessment of agricultural waste materials as HMs adsorbents, coupled with systematic identification of current research trends and gaps in adsorption applications.	Analysis of material quality inconsistency impacts on industrial applications, with evaluation of practical implementation challenges in global markets.

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Table 1 (*continued*)

Review	Focus and novelty	Contrast with this review
A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application (Chai et al., 2021)	Comparison of conventional and novel adsorbents in wastewater treatment, with a focus on recent advances in biochar and nanomaterials.	Evaluation of integration challenges with existing treatment infrastructure, with analysis of cost-benefit considerations in advanced material modifications.

developing and deploying innovative, eco-friendly technologies for the remediation of HMs pollution in water bodies.

2. Recent advancements in HMs removal from water with SBA

2.1. Structural and functional characteristics of sawdust

Sawdust-based adsorbents possess intrinsic characteristics that make them particularly well-suited for the removal of HMs. The lignocellulosic nature of SD contains a high proportion of functional moieties such as hydroxyl (–OH), methoxy (–OCH_3), and carboxyl (–COOH) groups, which facilitate strong interactions with metal cations via ion exchange, chelation, and hydrogen bonding (J. Jiang et al., 2024; Meez et al., 2021). These functional groups, especially when exposed through chemical activation or thermal treatments, act as high-affinity binding sites for divalent and trivalent metal ions like Pb(II), Cd(II), Cr(VI), and Cu(II) (El Hajam et al., 2023; Gong et al., 2019; Mutiara et al., 2019). The porous microstructure of SD allows for effective diffusion of contaminants, contributing to rapid kinetics, especially when equilibrium is reached within 30–60 min in optimized systems (Guo et al., 2020; Zhou et al., 2023).

Additionally, some SBA have demonstrated preferential adsorption behaviors, notably toward Pb(II), likely due to its larger ionic radius and lower hydration energy compared to other ions (Long et al., 2021). This selectivity is critical for applications involving complex matrices where multiple metals coexist. Advanced SBA formulations, particularly those modified with N-containing polymers or doped with iron oxides, offer redox-active sites that further enhance adsorption of Cr(VI) via partial reduction and precipitation (Ahmad et al., 2022). These structural and chemical attributes confirm SBA as a versatile, low-cost alternative to conventional adsorbents, with tunable selectivity and robust performance under a range of environmental conditions.

2.2. Chemical modification techniques

In recent years, significant advances have been made in the development and application of SBA for HMs removal from aqueous solutions. Table 2 provides an overview of these advances between 2019 and 2024, highlighting the diversity of SD sources, modification techniques, and their effectiveness in removing various HMs ions.

The analyzed studies explore various approaches to improve SD's adsorption capacity, with chemical modifications being the most frequent. These treatments typically involve acidic or alkaline processes, using reagents such as sulfuric acid (H_2SO_4), nitric acid (HNO_3), hydrochloric acid (HCl), sodium hydroxide (NaOH), and potassium hydroxide (KOH). The main objective is to increase the number of active sites on the SD surface and improve its porosity, thereby increasing its adsorption capacity (Kovacova et al., 2020).

Chemical treatments play an important role in enhancing the adsorbent properties of SD. Alkaline treatment with sodium hydroxide has been shown to significantly increase the adsorption capacity of Pb (II) and Zn(II) by introducing more reactive functional groups on the SD surface (Mutiara et al., 2019; Rani et al., 2022). Similarly, acid treatments improve adsorption capacity by removing impurities and creating new active sites, increasing efficiency in the adsorption of HMs such as chromium (VI) (Demcak et al., 2019; Kovacova et al., 2020).

The incorporation of functional groups such as hydroxyl, carboxyl, amine, and phosphate on the SD surface significantly improves its chemical adsorption capacity (Meister et al., 2019). For example, phosphorylation of natural SD has been shown to increase its affinity for toxic HMs such as Pb(II) and Cd(II), due to the strong binding between these ions and phosphate groups (Alhumaimess et al., 2019). Similarly, SD treated with H_2SO_4 creates additional active sites that enhance Cr (VI) ion adsorption (Özdeş et al., 2020). These treatments not only increase the number of active sites available for adsorption but also improve the adsorbent's selectivity for specific HMs (Ibrahim et al., 2022; Richards et al., 2019).

2.3. Nanoparticles and composite enhancements

The most advanced modification approaches utilize both organic polymers (e.g., chitosan (Kayalvizhi et al., 2022), polyaniline (PANI) (Tatu-Qassim et al., 2023), and poly(N-acryloyl-L-histidine) (PNAH) (Guo et al., 2020) and magnetite (Fe_3O_4) magnetic nanoparticles immobilized on SD (El-Sheikh et al., 2019), substantially enhancing its metal-ion adsorption capacity and, in the case of Fe_3O_4, enabling facile magnetic separation after treatment.

For example, chitosan-coated SD beads have demonstrated an adsorption capacity of up to 45 mg/g for Cu^{2+} and Ni^{2+} (Kayalvizhi et al., 2022). Additionally, a polyaniline (PANI) SD composite achieved 98 % removal of Pb^{2+} at pH 5 (Tatu-Qassim et al., 2023). Meanwhile, modification with poly(N-acryloyl-L-histidine) (PNAH) yielded an adsorption capacity of up to 202 mg/g for Cu^{2+} (Guo et al., 2020). These studies demonstrate that the incorporation of organic polymers into SD enhances its efficiency in capturing various metal ions. Collectively, such modifications enable the tuning of adsorption affinity and capacity according to the specific target metal.

The incorporation of nanomaterials into SBA significantly enhances their performance by introducing novel physicochemical properties. For instance, Fe_3O_4 nanoparticles impart magnetic properties that facilitate post-treatment separation, thus improving the reusability of the adsorbent (El-Sheikh et al., 2019; Tamjidi et al., 2019). These composites not only increase surface area but also contribute to electron transfer, enhancing redox interactions, especially in the removal of species such as Cr(VI) and nitroaromatic compounds. Ahmad et al. (2022) demonstrated that iron and nitrogen doped biochar composites exhibited superior Cr(VI) and nitrobenzene removal efficiencies via carbothermal reduction, highlighting the synergistic effect of nanoparticle inclusion and bio-based supports (Ahmad et al., 2022). Similarly, Fe_3O_4-doped SBA showed enhanced adsorption through a combination of electrostatic attraction, complexation, and redox activity with%removal > 90 % de Cr(VI) (El-Sheikh et al., 2019). These improvements are particularly relevant for developing multifunctional materials tailored to multi-contaminant scenarios in water treatment.

The development of composite materials combining SD with substances like Fe_3O_4 or silver nanoparticles has resulted in notable improvements in adsorption performance. These composite materials benefit from synergistic effects, offering greater stability, increased surface area, and better interaction with HMs ions (El-Sheikh et al., 2019; Sabermahani and Ganjehkaviri, 2021). For example, the incorporation of layered double hydroxides (LDH) into SD provides additional active sites, improving Pb(II) adsorption (Gong et al., 2019). Similarly, SD modified with iron oxide nanoparticles demonstrated enhanced removal capacity for Pb(II) and Cr(VI), thanks to increased surface area (Praipipat et al., 2023; Tatu-Qassim et al., 2023). These advanced nanocomposites represent a promising direction for developing highly effective adsorbents with improved kinetics for water treatment applications (Choudhury et al., 2024).

The various chemical and biochemical modification strategies for enhancing sawdust's heavy-metal adsorption capacity are summarized in Fig. 3. The figure illustrates acidic treatments that remove impurities and generate new active sites. It also depicts phosphorylation and

Table 2
Recent advances in SBA for HMs removal from aqueous solutions (2019–2024).

SBA	HMs target	Equilibrium time (min)	Q_m (mg/g)	Best fitting isotherm	Best fitting reaction order model	Main adsorption mechanism	Reference
Ackee wood SD	Cd(II)	30	2.48	–	–	Ion exchange	(Saliu et al., 2022)
Alkali (NaOH) and acid (H_2SO_4) modified wood SD	Cd(II)	120	9.6711	Freundlich	PSO	Ion exchange	(Faisal et al., 2024)
Alkali (NaOH) modified banana shrub wood SD	Cd(II)	720	19.11	Langmuir	–	Surface complexation	(Long et al., 2021)
Rice husk mixed with bamboo wood SD	Cd(II)	126	73.8	–	–	Ion exchange	(Kwikima et al., 2022)
Acid (maleic acid) modified pine wood SD	Cd(II)	35	180.4	–	PSO	Ion exchange	(Hashem et al., 2020)
PAMAM-TiO_2 modified oak wood SD	Cd(II)	45	188	Freundlich	PSO	Surface complexation	(Ibrahim et al., 2022)
Phosphorylated wood SD	Cd(II)	180	284.1	Freundlich	PSO	Electrostatic attraction	(Alhumaimess et al., 2019)
PAMAM-TiO_2 modified oak wood SD	Co(II)	30	196	Freundlich	PSO	Surface complexation	(Ibrahim et al., 2022)
Mango wood SD	Cr(III)	120	0.969	–	–	Ion exchange	(Kumari et al., 2023)
Detergent powder modified wood SD	Cr(III)	120	4.69	Langmuir	PSO	Electrostatic attraction	(Afzaal et al., 2022)
Phosphorylated wood SD	Cr(III)	180	284.1	Freundlich	PSO	Electrostatic attraction	(Alhumaimess et al., 2019)
Acid (H_2SO_4 and HCOH) modified wood SD	Cr(VI)	20	8.84	Freundlich	PSO	Surface complexation	(Chakraborty et al., 2021)
Acid (H_2SO_4) modified sal wood SD	Cr(VI)	180	39.8	Langmuir	PSO	Electrostatic attraction	(Choudhury et al., 2024)
Acid (H_2SO_4) and alkali (NaOH) modified pine wood SD	Cr(VI)	60	45.25	Langmuir	PSO	Surface complexation	(Sirusbakht et al., 2024)
Moroccan Atlas cedar wood SD	Cr(VI)	60	48.31	Langmuir	PSO	Surface complexation	(El Hajam et al., 2023)
Acid (H_2SO_4) modified oak wood SD	Cr(VI)	240	100	Freundlich	–	Electrostatic attraction	(Özdeş et al., 2020)
TEPA-BCTTC modified metasequoia wood SD	Cr(VI)	–	189.32	–	–	Surface complexation	(Wu et al., 2023)
PAMAM-TiO_2 modified oak wood SD	Cr(VI)	30	190	Freundlich	PSO	Surface complexation	(Ibrahim et al., 2022)
Organosolv modified spruce wood raw SD	Cr(VI)	1440	318.3	SIPS	PSO	Electrostatic attraction	(Politi and Sidiras, 2020)
Keekar wood SD	Cu(II)	15	1.85	Langmuir	PSO	Ion exchange	(Aachhera et al., 2022)
FeO(OH) modified Monterey pine wood SD	Cu(II)	120	0.82	Langmuir	PSO	Ion exchange	(Orozco et al., 2023)
Spruce wood SD	Cu(II)	60	0.9	–	–	Ion exchange	(Kovacova et al., 2019)
Wood SD	Cu(II)	1080	2.9	–	–	Surface complexation	(Richards et al., 2019)
Wood SD	Cu(II)	120	4.33	Langmuir	–	Surface complexation	(Ulfa et al., 2019)
Acid (H_3PO_4) and bentonite modified pine wood SD	Cu(II)	120	4.9	–	PSO	Surface complexation	(Del Sole et al., 2023)
Alkali (NaOH) modified spruce wood SD	Cu(II)	1440	4.9	Langmuir	–	Ion exchange	(Demcak et al., 2019)
Chitosan modified wood SD	Cu(II)	70	7.32	Freundlich	PSO	Surface complexation	(Kayalvizhi et al., 2022)
Ether modified koroi wood SD	Cu(II)	60	9.4	Langmuir	PSO	Chelation	(Nurnabi et al., 2020)
Alkali (KOH) modified cherry wood SD	Cu(II)	1440	11.06	Freundlich	–	Surface complexation	(Kovacova et al., 2020)
Alkali (NaOH) modified banana shrub wood SD	Cu(II)	720	13.98	Langmuir	–	Surface complexation	(Long et al., 2021)
Pine SD	Cu(II)	15	14.9	Freundlich	–	Ion exchange	(Mannaï et al., 2022)
PNAH grafted birch wood SD	Cu(II)	60	95.7	–	PSO	Surface complexation	(Guo et al., 2020)
PAMAM-TiO_2 modified oak wood SD	Cu(II)	30	198	Freundlich	PSO	Surface complexation	(Ibrahim et al., 2022)
AMPS-AA modified fir wood SD	Cu(II)	45	253.37	Langmuir	PSO	Electrostatic attraction	(Zhou et al., 2023)
Alkali (NaOH) modified spruce wood SD	Fe	1440	4.3	Langmuir	–	Ion exchange	(Demcak et al., 2019)
Acid (HNO_3) and alkali (NaOH) modified wood SD	Hg(II)	120	528	Langmuir	PSO	Electrostatic attraction	(Bouzid et al., 2024)
PAMAM-TiO_2 modified oak wood SD	Mn(VII)	30	198	Freundlich	PSO	Surface complexation	(Ibrahim et al., 2022)
Mango wood SD	Ni(II)	120	1.828	–	–	Ion exchange	(Kumari et al., 2023)
Acid (H_3PO_4) and bentonite modified pine wood SD	Ni(II)	120	5.2	–	PSO	Surface complexation	(Del Sole et al., 2023)
Chitosan modified wood SD	Ni(II)	70	6.92	Freundlich	PSO	Surface complexation	(Kayalvizhi et al., 2022)

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Table 2 (*continued*)

SBA	HMs target	Equilibrium time (min)	Q_m (mg/g)	Best fitting isotherm	Best fitting reaction order model	Main adsorption mechanism	Reference
Acid (H_2SO_4) modified Caribbean pine wood SD	Ni(II)	60	7.274	Freundlich	PSO	Electrostatic attraction	(Sinyeue et al., 2022)
Alkali (NaOH) modified jackfruit wood SD	Pb(II)	1440	4.43	Freundlich	PSO	Ion exchange	(Mutiara et al., 2019)
Eucalyptus wood SD	Pb(II)	50	4.8	Langmuir	PSO	Ion exchange	(Tejada-Tovar et al., 2021)
Ether modified koroi wood SD	Pb(II)	60	17.37	Langmuir	PSO	Chelation	(Nurnabi et al., 2020)
TEPA-BCTTC modified metasequoia wood SD	Pb(II)	–	22.92	–	–	Surface complexation	(Wu et al., 2023)
Mg-Al-LDHs modified eucalyptus wood SD	Pb(II)	180	31.4	Freundlich	PSO	Ion exchange	(Gong et al., 2019)
Narra wood SD	Pb(II)	200	47.17	Freundlich	PSO	Electrostatic attraction	(Praipipat et al., 2023)
Alkali (NaOH) modified banana shrub wood SD	Pb(II)	720	47.66	Langmuir	–	Surface complexation	(Long et al., 2021)
Fe_3O_4 modified olive wood SD	Pb(II)	180	49	Langmuir	–	Surface complexation	(El-Sheikh et al., 2019)
Acid (HNO_3) and alkali (NaOH) modified dibetou wood SD	Pb(II)	60	61.73	Langmuir	PSO	Ion exchange	(El Hajam et al., 2020)
Mango wood SD	Pb(II)	120	74.6	–	–	Ion exchange	(Kumari et al., 2023)
Phosphorylated wood SD	Pb(II)	180	198.51	Freundlich	PSO	Electrostatic attraction	(Alhumaimess et al., 2019)
PNAH grafted birch wood SD	Pb(II)	60	241.8	–	PSO	Surface complexation	(Guo et al., 2020)
AMPS-AA modified fir wood SD	Pb(II)	45	257.34	Freundlich	PSO	Electrostatic attraction	(Zhou et al., 2023)
Eastern spruce wood SD	Pb(II)	60	278	Freundlich	–	Ion exchange	(Bilgin and Ateş, 2021)
Acid (HCl) and PANI modified coco wood SD	Pb(II)	15	738.9	–	–	Electrostatic attraction	(Tatu-Qassim et al., 2023)
Ag modified wood SD	Tl(I)	60	26.11	Freundlich	PSO	Electrostatic attraction	(Sabermahani and Ganjehkaviri, 2021)
Hornbeam wood SD	Zn(II)	10	0.85	–	–	Ion exchange	(Kovacova, 2019)
Wood SD	Zn(II)	1080	3	–	–	Surface complexation	(Richards et al., 2019)
Alkali (NaOH) modified hornbeam wood SD	Zn(II)	1440	4.82	Langmuir	–	Ion exchange	(Demcak et al., 2019)
Keekar wood SD	Zn(II)	20	7.49	Freundlich	PSO	Ion exchange	(Aachhera et al., 2022)
Alkali (KOH) modified hornbeam wood SD	Zn(II)	1440	10.31	Langmuir	–	Surface complexation	(Kovacova et al., 2020)
Beech wood SD	Zn(II)	90	17.92	–	–	Ion exchange	(Michael Ogunjobi et al., 2021)
Acid (H_2SO_4) Indian rose wood SD	Zn(II)	120	227.27	Freundlich	PSO	Electrostatic attraction	(Rani et al., 2022)
AMPS-AA modified fir wood SD	Zn(II)	45	241.23	Langmuir	PSO	Electrostatic attraction	(Zhou et al., 2023)

LDHs: layered double hydroxides.
PNAH: poly(N-acryloyl-L-histidine.
PAMAM: polyamidoamine.
TEPA-BCTTC: tetraethylene-pentamine-biscarboxymethyl trithiocarbonate.
AMPS-AA: acrylic acid-2-acrylamido-2-methylpropanesulfonic acid.
PANI: polyaniline.
PSO: Pseudo-second-order.

organic-polymer grafting to introduce specific binding moieties, and the incorporation of nanoparticles. By combining these techniques, modified sawdust achieves higher adsorption capacities and selectivities tailored to different target metals and water-treatment scenarios (Kovacova et al., 2020; Mutiara et al., 2019). Fig. 3 provides a visual guide to understanding how each type of modification contributes to the overall performance of the adsorbent.

2.4. Physicochemical treatments (pyrolysis and hydrothermal carbonization)

While chemical modifications of SBA—such as acid/base activation, oxidation, and grafting—have received considerable attention (Mutiara et al., 2019; Özdeş et al., 2020), physicochemical treatments like pyrolysis and hydrothermal carbonization (HTC) remain underutilized despite their unique advantages. Pyrolysis transforms SD into biochar through thermal decomposition in an oxygen-limited environment, resulting in a porous carbonaceous matrix with enhanced aromaticity and stability (Chan et al., 2019). This process leads to significant improvements in specific surface area, thermal resistance, and the formation of oxygen-containing surface groups capable of complexing metal ions (Ahmad et al., 2022). In contrast, HTC occurs in water at subcritical conditions (180–250 °C), producing hydrochar with a high density of functional groups such as hydroxyl and carboxyl, favorable for adsorption via hydrogen bonding and ion exchange (Khanzada et al., 2024).

Ahmad et al. (2022) demonstrated that iron- and nitrogen-doped biochar composites prepared via carbothermal reduction exhibited superior Cr(VI) and nitrobenzene removal efficiencies, highlighting the synergistic effect of nanoparticle inclusion and bio-based supports (Ahmad et al., 2022). More recently, Ahmad et al. (2024) investigated the performance of Fe–N co-doped biochar for the adsorption of 2,4,6-trichlorophenol and revealed that such carbonized systems exhibited high sorption capacities due to π–π interactions, inner-sphere complexation, and redox activity at the interface. They also emphasized that

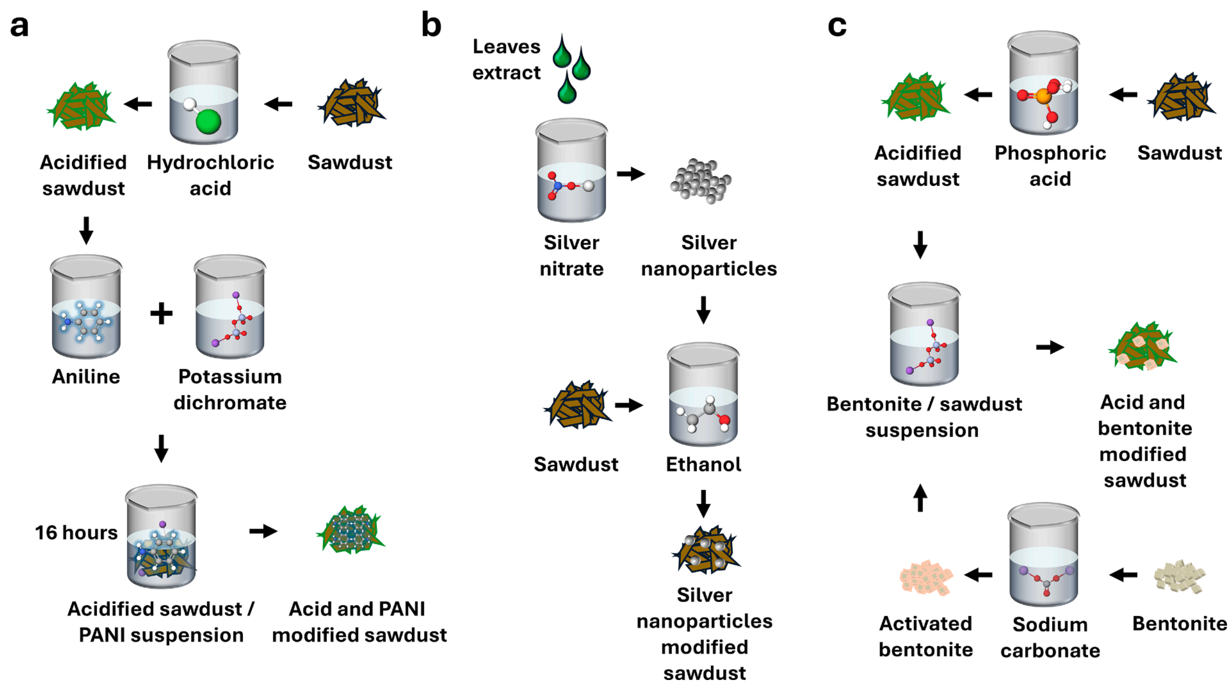

Fig. 3. Preparation procedures of different SBA: (a) acid (HCl) and PANI modified coco wood SBA; (b) Ag modified wood SBA; (c) Acid (H_3PO_4) and bentonite modified pine Wood SBA.

post-pyrolysis doping enhanced electron donor–acceptor interactions and increased the abundance of active sites (Ahmad et al., 2024).

The development of such materials through physicochemical treatments aligns with green chemistry principles by minimizing chemical inputs while maximizing structural and functional enhancements. These methods could be further integrated with nanoparticle loading and polymer grafting to produce SBA with multi-modal adsorption capabilities.

2.5. Multi-contaminant removal and selectivity

These investigations encompass a wide range of HMs, including commonly studied elements such as Pb, Cu, Cd, Cr, Zn, and Ni, as well as less frequently studied but equally concerning elements like Hg and Mn, often depending on specific regional environmental concerns or industrial activities (Demcak et al., 2019; Li et al., 2022; Yang et al., 2022). For instance, Hg contamination has been extensively reported in coastal wetlands (Li et al., 2022), while Mn accumulation is significant in groundwater sources used for human consumption in Bangladesh (Rushdi et al., 2023).

In real water treatment scenarios, where multiple HMs coexist, the adsorbent must exhibit selective adsorption capabilities. Several studies have demonstrated that SD-based materials tend to preferentially adsorb certain ions over others when exposed to multi-metal solutions. For example, it has been observed that Pb(II) is more strongly adsorbed compared to Cu(II) and Cd(II) ions under competitive conditions (Özdeş et al., 2020; Sirusbakht et al., 2024). This selective adsorption behavior is primarily influenced by factors such as the hydrated ionic radius, ionic charge, and the nature of the functional groups introduced on the SD surface through chemical modification, which together determine the affinity and selectivity toward specific metal (Kovacova et al., 2019; Nighojkar et al., 2022; C. Wang et al., 2020).

2.6. Adsorption mechanisms, kinetics and isotherms

The characterization of these modified SBAs is essential to understand their physicochemical properties and the sorption mechanisms involved. Scanning electron microscopy (SEM) is widely used to examine surface morphology and porosity of adsorbents, providing valuable data on structural changes resulting from various modifications (Ighalo and Adeniyi, 2020). Fourier transform infrared spectroscopy (FTIR) is another commonly employed technique to identify functional groups on the adsorbent surface. These functional groups play a fundamental role in the adsorption process, and their identification helps understand HMs adsorption mechanisms (Chakraborty et al., 2022). X-ray diffraction (XRD) is used to analyze the crystalline structure of adsorbents, particularly those modified with nanoparticles, offering insight into the structural arrangement and phase composition of materials (Ali et al., 2022).

The thermodynamic aspects of chemical adsorption indicate that the process is generally endothermic, suggesting that higher temperatures can increase adsorption efficiency. This has been demonstrated in studies where Cu(II) and Ni(II) adsorption in SD-chitosan nanocomposite microspheres increased with temperature, reflecting the endothermic nature of chemisorption (Kayalvizhi et al., 2022). Adsorption isotherms describe how HMs ions are distributed between the liquid phase and solid phase (adsorbent) at equilibrium and provide important information about adsorption capacity and mechanism (Tran et al., 2021).

The Langmuir isotherm model assumes that adsorption occurs in a monolayer on a surface with a finite number of identical and energetically equivalent sites. This model is particularly suited for describing chemisorption processes, where the adsorption sites are homogeneous and have uniform affinity for the adsorbate molecules (Swenson and Stadie, 2019). Several studies have confirmed that the adsorption of HMs such as Pb(II), Cd(II), and Cr(VI) onto chemically modified SD fits well with the Langmuir isotherm, indicating that monolayer chemisorption is the predominant mechanism. For instance, the adsorption of Cd(II) onto acid-activated cedar SD was best described by the Langmuir model, with a reported maximum adsorption capacity (Q_m) of 50.63 mg/g, and a correlation coefficient (R^2) greater than 0.99, confirming a homogeneous monolayer distribution (El Hajam et al., 2023). Likewise, the adsorption of Pb(II) onto phosphorylated raw SD demonstrated an excellent fit to the Langmuir model, achieving a Q_m of 178.57 mg /g and an R^2 of 0.998, further supporting that chemisorption governs the adsorption process (Alhumaimess et al., 2019).

The Freundlich isotherm is an empirical model that describes adsorption on heterogeneous surfaces, where adsorption sites possess varying affinities for the adsorbate (Al-Ghouti and Da'ana, 2020). Unlike the Langmuir model, the Freundlich model does not assume a uniform surface or monolayer formation; instead, it accounts for multilayer adsorption and progressive site occupancy as the adsorbate concentration increases (J. Wang and Guo, 2020). Several studies have reported that the adsorption of metal ions onto modified SD materials follows the Freundlich isotherm, supporting the idea of surface heterogeneity. For example, the adsorption of Cu(II) and Zn(II) onto base-treated jackfruit SD showed a good fit to the Freundlich model, with correlation coefficients (R^2) above 0.97, suggesting multilayer adsorption and diverse binding energies (Mutiara et al., 2019; Rani et al., 2022). Similarly, the adsorption of Cr(VI) onto sulfuric acid-modified oak SD exhibited a Freundlich constant (n) greater than 1, indicating favorable adsorption and the presence of heterogeneous sites on the surface (Özdeş et al., 2020).

Adsorption kinetics provides essential information about the rate of adsorption and the underlying mechanisms involved (Praipipat et al., 2023). Understanding adsorption kinetics is crucial for the design and optimization of water treatment systems (El Hajam et al., 2020). In most studies involving heavy metal (HM) adsorption onto modified SD, the kinetic data fit well with the pseudo-second-order model, indicating that chemisorption is the dominant mechanism. This model suggests that the rate-limiting step is controlled by chemical adsorption, involving valence forces through the sharing or exchange of electrons between the adsorbent and adsorbate (Patro et al., 2024). For example, Pb(II) adsorption onto phosphorylated SD was best fitted by the pseudo-second-order model, with a high correlation coefficient ($R^2 >$ 0.99), confirming chemisorption as the primary interaction mechanism (Alhumaimess et al., 2019). Similarly, the adsorption of Cr(VI) onto acid-treated SD also showed conformity with this kinetic model, supporting the dominance of chemical binding processes (Sirusbakht et al., 2024).

In some cases, the adsorption process is influenced by intraparticle diffusion, especially when the adsorbate must diffuse into the adsorbent pores (Mudhoo et al., 2024). This is observed in studies where adsorption kinetics are initially rapid, followed by a slower phase as the adsorbate diffuses into the adsorbent particles (Mohamed Nasser et al., 2024). For example, in Cu(II) and Ni(II) adsorption in SD-chitosan nanocomposite microspheres, intraparticle diffusion plays an important role in the overall adsorption process, and kinetics are best described by a combination of pseudo-second-order and intraparticle diffusion models (Kayalvizhi et al., 2022; Sinyeue et al., 2022).

Additionally, the Elovich kinetic model, commonly applied to chemisorption processes on heterogeneous surfaces, describes scenarios where the adsorption rate decreases exponentially as surface coverage increases (Kovacova et al., 2019). This model has been successfully applied to explain the adsorption kinetics of Pb(II) and Cd(II) on modified SD materials. For instance, the adsorption of Cd(II) onto blended bamboo SD/rice husk composites followed the Elovich model, highlighting the influence of surface heterogeneity and the chemisorption mechanism (Kwikima et al., 2022). Likewise, Pb(II) adsorption onto chemically modified SD showed a good fit with the Elovich model, further indicating that the adsorption sites possess varying activation energies and confirming a heterogeneous chemisorption process (Long et al., 2021).

Solution pH is a critical factor influencing the adsorption capacity of SBA, as it affects both the surface charge of the adsorbent and the speciation of heavy metal (HM) ions (Meez et al., 2021; Ngeno et al., 2022). Under acidic conditions (typically pH 3–5), protonation of surface functional groups such as hydroxyl and carboxyl groups increases the electrostatic attraction between the positively charged HM ions and the negatively charged SD surface, enhancing adsorption efficiency (Meez et al., 2021; Ngeno et al., 2022). For example, maximum adsorption of Pb(II) and Zn(II) onto modified SD has been reported around pH 5, where surface protonation is optimal (Rani et al., 2022; Zhou et al., 2023). However, at very low pH values (below 3), hydronium ions (H_3O^+) compete with metal ions for active binding sites, leading to a decrease in adsorption capacity (Adegoke et al., 2022). On the other hand, at higher pH levels (above 6–7), HM ions such as Pb(II) and Cu(II) can precipitate as metal hydroxides (e.g., $Pb(OH)_2$), which can interfere with adsorption measurements and artificially lower the observed adsorption capacities (Ibrahim et al., 2022; Nurnabi et al., 2020). Therefore, optimizing the solution pH is essential to accurately assess the adsorption behavior and maximize removal efficiency.

In summary, the adsorption potential of SD has been significantly enhanced through various modification techniques, ranging from simple chemical treatments to advanced nanocomposite development (Mallakpour et al., 2021). These modifications introduce additional functional groups, increase surface area, or incorporate advanced materials, thereby improving adsorption capacity, selectivity, and overall performance. The integration of nanomaterials (such as magnetic nanoparticles, metal oxides, and carbon-based materials) has not only increased adsorption capacity but also endowed the material with additional functionalities such as magnetic separation and antimicrobial properties (Mallakpour et al., 2021; Nighojkar et al., 2022).

Adsorption mechanisms on modified SD include both chemical adsorption (via hydrogen bonding, species replacement, and complexation) and physical adsorption (through electrostatic attractions). In Fig. 4 of the manuscript, adapted from Fei and Hu (Fei and Hu, 2022), it is illustrated how the –OH, –COOH and phenolic functional groups of the modified SD adsorbent form hydrogen bonds, undergo proton–metal ion exchange, and directly coordinate metal ions via surface complexation, while the charged surface and van der Waals forces ensure pH-dependent physical retention of the ions. To support these mechanisms, kinetic and isotherm modeling studies have been extensively applied. All studies summarized in Table 2 that performed kinetic evaluations showed correlation with the pseudo-second-order (PSO) model, indicating that chemisorption is the predominant rate-limiting step in SBA systems. A notable example is NaOH-modified jackfruit wood SD for Pb(II) adsorption, which exhibited excellent fit to the PSO

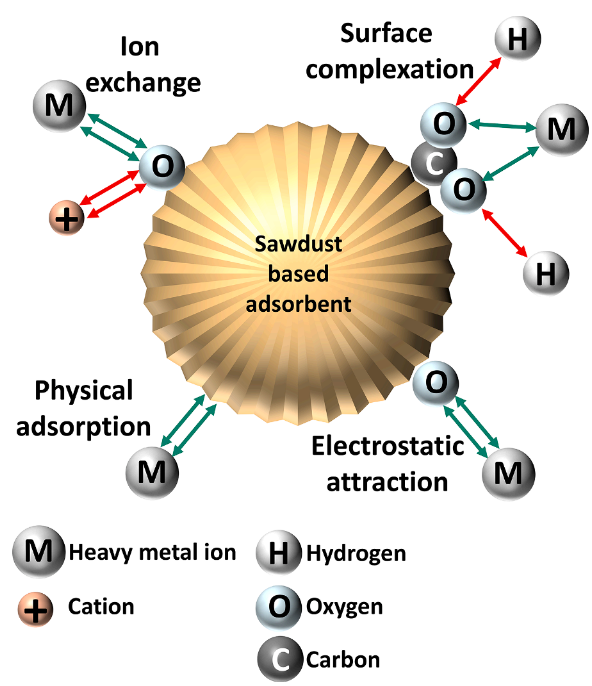

Fig. 4. Schematic representation of HM's adsorption mechanisms on SD. The diagram shows chemical adsorption through hydrogen bonding, species replacement, and complexation, alongside physical adsorption via electrostatic attractions (adapted from Fei and Hu 2022 (Fei and Hu, 2022)).

model (Mutiara et al., 2019). Likewise, phosphorylated SD for Cd(II) and Pb(II) adsorption also followed PSO kinetics (Alhumaimess et al., 2019), as did nano zero-valent iron supported SD for Cr(VI) removal (Choudhury et al., 2024).

Equilibrium isotherm modeling further supports these findings. The Langmuir model, which assumes monolayer adsorption on homogeneous active sites, was frequently observed in Fe_3O_4-modified olive wood SD for Pb(II) and KOH-treated hornbeam SD for Zn(II) (Kovacova et al., 2019), suggesting chemisorption on uniform sites. In contrast, Freundlich isotherms, which describe multilayer adsorption on heterogeneous surfaces, provided a better fit for Cd(II) and Pb(II) adsorption onto phosphorylated SD (Alhumaimess et al., 2019) and SD treated with alkali (Mutiara et al., 2019) or acid (Özdeş et al., 2020), highlighting the coexistence of chemisorption and physisorption mechanisms. Notably, only organosolv-modified spruce wood SD showed a preferential fit to the SIPS (Langmuir–Freundlich) isotherm model for Cr(VI) adsorption (Alhumaimess et al., 2019; Choudhury et al., 2024; Kovacova et al., 2019; Mutiara et al., 2019; Politi and Sidiras, 2020). This hybrid model combines elements of Langmuir (monolayer adsorption) and Freundlich (heterogeneous surface energy distribution), making it particularly useful for systems with chemically modified heterogeneous surfaces.

Additionally, complementary kinetic models such as the Elovich model and intraparticle diffusion have been employed to describe the adsorption process on heterogeneous SBA surfaces in greater detail, especially in studies involving Cu(II), Ni(II), and Cr(VI) using chitosan- and detergent-modified SD (Afzaal et al., 2022; Kayalvizhi et al., 2022). In some cases, comprehensive kinetic and isotherm studies have incorporated multiple models, including external diffusion models, to better describe adsorption mechanisms.

The coexistence of chemisorption and physisorption mechanisms arises because sorption is a complex process involving multiple, non-exclusive stages. In this context, kinetic and isotherm modeling not only helps identify the dominant type of interaction but also reveals the critical stage or rate-limiting step of the adsorption process essential information for the efficient design of SBA-based water treatment systems (Alhumaimess et al., 2019; Choudhury et al., 2024; El-Sheikh et al., 2019; Kovacova et al., 2020; Mutiara et al., 2019; Özdeş et al., 2020; Politi and Sidiras, 2020; Sinyeue et al., 2022).

These findings not only support theoretical adsorption mechanisms but also provide predictive tools for optimizing operating conditions in real-world water treatment applications (Afzaal et al., 2022; Alhumaimess et al., 2019; El-Sheikh et al., 2019). It is worth highlighting that kinetic and isotherm modeling is complemented by the physicochemical characterization of sorbent materials before and after exposure to contaminants. Spectroscopic analyses such as FTIR allow for the identification of functional groups involved in adsorption (Aachhera et al., 2022; Sabermahani and Ganjehkaviri, 2021; Saliu et al., 2022). Similarly XRD provides information about the crystalline structure of the materials, while X-ray photoelectron spectroscopy (XPS) offers insights into surface composition and oxidation states associated with chemical sorption mechanisms (Bilgin and Ateş, 2021; Saliu et al., 2022).

Even simple measurements, such as pH changes before and after the adsorption process, can be correlated with specific mechanisms, such as the replacement of OH^- groups by ions HMs on the SD surface. For example, a decrease in pH may indicate proton release during the formation of chemical complexes, while an increase could suggest ion exchange mechanisms where protons are displaced by ions HMs (Alhumaimess et al., 2019; Choudhury et al., 2024; El-Sheikh et al., 2019).

While SD adsorbents have shown remarkable laboratory results in treating water contaminated with HMs like Pb(II), Cd(II), Zn(II), and Cr (VI) (Long et al., 2021; Orozco et al., 2023), scaling up for industrial applications presents challenges including the need for large quantities of material, adsorbent regeneration, and waste management (Gong et al., 2019; Wu et al., 2023). Nevertheless, successful pilot studies and advances in composite materials suggest these obstacles can be overcome, making SBA viable for diverse contaminated water sources such as industrial effluent, mine drainage, and agricultural runoff (Kumari et al., 2023; Praipipat et al., 2023).

Based on the comprehensive review of recent advances in SBA, it is evident that these materials offer considerable promise for heavy metal removal from aqueous solutions, especially when subjected to targeted chemical modifications. Numerous studies have shown that modified SD can substantially increase adsorption capacity. For instance, AA-SW-AMPS modified fir wood SD achieved adsorption capacities of 257.34 mg/g for Pb(II), 253.37 mg/g for Cu(II), and 241.23 mg/g for Zn(II) (Zhou et al., 2023), while phosphorylated wood SD reached up to 284.1 mg/g for Cd(II) and Cr(III) (Alhumaimess et al., 2019). In comparison, untreated SD exhibits much lower capacities, typically under 5 mg/g for most metals (Demcak et al., 2019; Kovacova et al., 2019; Ulfa et al., 2019). The increase in adsorption efficiency is attributed to the introduction of functional groups (e.g., phosphate, sulfonic acid) and enhancement of surface area and porosity (Alhumaimess et al., 2019; Özdeş et al., 2020; Zhou et al., 2023).

These modifications, despite involving basic reagents such as NaOH, H_2SO_4, or HCl, remain cost-effective due to the low price and accessibility of both the raw material and treatment agents (Mutiara et al., 2019; Udokpoh and Nnaji, 2023). Moreover, SD is a waste byproduct from the wood industry, offering significant economic and environmental benefits under circular economy frameworks (Nighojkar et al., 2022; Udokpoh and Nnaji, 2023). Regarding regeneration, studies report that materials like PNAH-grafted birch wood SD can maintain over 90 % efficiency after three adsorption-desorption cycles using acid-EDTA regeneration (Guo et al., 2020), supporting their long-term applicability. Taken together, these findings reinforce that SBA are not only efficient for HMs removal, but also viable from a cost and sustainability perspective for real-world water treatment scenarios.

To fully assess the viability of SBA for large-scale water treatment, the following section presents a systematic evaluation of their strengths, weaknesses, opportunities, and threats (SWOT analysis). This evaluation will help identify key advantages to leverage, challenges to address, potential opportunities for advancement, and possible obstacles to implementation in real-world scenarios.

3. SBA SWOT analysis for HMs removal from water

3.1. Strengths

Sawdust is a low-cost and widely available material due to its origins as a wood industry byproduct. Hence, using SD for water treatment could help repurpose waste while offering a potentially sustainable and economic adsorbent option (Chan et al., 2019; Udokpoh and Nnaji, 2023). However, its overall economic viability depends on factors like processing methods, treatment efficiency, and regeneration potential. To properly evaluate its cost-effectiveness, future work should include a techno-economic analysis and a comparison with common adsorbents such as activated carbon or biochar, considering factors like scalability and long-term performance.

The versatility of SD as an adsorbent material represents a significant practical advantage. As demonstrated throughout this review, SD derived from diverse wood species, including pine, oak, beech, eucalyptus, and tropical hardwoods, has been successfully employed for HMs adsorption. This cross-species applicability enables the utilization of locally available wood resources, substantially reducing transportation costs and carbon footprint associated with adsorbent production (Cheng et al., 2020). Several studies specifically highlighted the use of locally available SD as their adsorbent material (Demcak et al., 2019; El Hajam et al., 2020). Rather than requiring specialized wood sources from distant regions, water treatment facilities can potentially leverage locally abundant SD materials. While the natural variations in wood composition across different species do exist, this diversity can be strategically harnessed to match specific adsorbents with target contaminants or treatment scenarios (Kaczorowska and Bożejewicz, 2024), creating opportunities for optimized, location-specific water treatment solutions.

Although SD can be used without further treatment, the ease of modification enhances SD's potential. Simple chemical treatments, such as acid or alkali modifications, can significantly improve adsorption capacity. For instance, H_2SO_4 and KOH treatments have shown substantial improvements in performance (Kovacova et al., 2020; Özdeş et al., 2020). These modifications are straightforward and feasible across various settings, from small-scale to industrial applications.

Nanotechnology also opens new avenues for enhancing SBA. For example, Fe_3O_4 modified olive wood SD exhibits magnetic properties that not only enhance adsorption capacity but also facilitate easier separation of the adsorbent post-treatment (El-Sheikh et al., 2019). Similarly, PAMAM-TiO_2 modified oak wood SD displays antimicrobial properties, adding value in complex water treatment scenarios, particularly in regions with limited access to comprehensive systems (Ibrahim et al., 2022).

SBA exhibit remarkable effectiveness across a wide range of conditions, making them a robust solution for various applications. While optimal performance is often achieved within specific pH and temperature ranges (Sable et al., 2024), studies show that these adsorbents can remove HMs effectively under broader conditions. For instance, Ag modified wood SD has successfully removed Tl(I) across a pH range of 2.5 to 7.5 (Sabermahani and Ganjehkaviri, 2021), while chitosan modified wood SD has been effective in removing Cu(II) and Ni(II) within a pH range of 5 to 10 (Kayalvizhi et al., 2022). In both cases, adsorption improved with increasing temperatures up to 48–50 °C. This robustness ensures that SBA are well-suited for diverse environmental and industrial applications, especially where conditions may be variable or difficult to control.

The potential for regeneration and reuse of SBA opens up opportunities for developing sustainable, long-term water treatment solutions path toward sustainable, long-term water treatment solutions. By applying various regeneration techniques such as magnetic separation, thermal desorption, and chemical desorption, the reusability of these adsorbents could be improved, enhancing both environmental and economic benefits (Baskar et al., 2022). Research has demonstrated that low-cost adsorbents, such as agricultural wastes, can be effectively regenerated and reused for multiple adsorption-desorption cycles (El Messaoudi et al., 2024). For example, AMPS-AA modified fir wood SD was regenerated using HCl desorption, followed by NaOH neutralization and water washing (Zhou et al., 2023), while PNAH grafted birch wood SD was regenerated through acid-EDTA treatment, followed by carbonate neutralization and water washing (Guo et al., 2020). Notably, both adsorbents maintained efficiency above 90 % for Pb(II) removal even after 3 cyclic runs, demonstrating their potential for sustainable use in water treatment applications. Effective regeneration methods are crucial for the economic feasibility of these adsorbents, as their repeated use can reduce operational costs and ensure their viability in large-scale applications (Gkika et al., 2022).

The versatility of SBA in removing a wide range of HMs pollutants, such as Cu(II), Pb(II), Zn(II), Cr(VI), Cd(II), and Hg(II), highlights their significant potential for developing multifunctional water treatment solutions (Mallakpour et al., 2021). This broad applicability is complemented by their capacity to adsorb a diverse range of organic pollutants, including dyes and pharmaceuticals, due to the presence of various functional groups and the porous structure inherent in SD (Liu et al., 2023). This multifaceted adsorption capability enables SBA to address both common and specialized contaminants simultaneously, making them exceptionally versatile for comprehensive industrial wastewater treatment systems (Anastopoulos et al., 2022).

Furthermore, the ability to handle multiple types of pollutants with a single type of adsorbent simplifies the treatment process, reducing the need for multiple treatment stages and potentially lowering operational costs (Hlongwane et al., 2019). Several studies reporting differential affinity and competitive adsorption behavior. For example, NaOH-treated banana shrub wood demonstrated a capacity to adsorb Cu (II), Pb(II), and Cd(II) in a single reaction system, with Pb(II) consistently showing the highest uptake, likely due to its favorable hydration energy and radius (Long et al., 2021).

More complex systems incorporating layered double hydroxides (LDHs), polyamidoamine (PAMAM), or bifunctional groups have further improved multimetal selectivity. SBA modified with AMPS-AA copolymers exhibited high adsorption capacities for Pb(II), Cu(II), and Zn (II), reaching up to 257.34 mg/g for Pb(II), indicating strong ion-specific interactions enabled by the polymer's sulfonic and carboxylic groups (Zhou et al., 2023). Similarly, PNAH-modified birch wood SBA achieved efficient removal of Cu(II) and Pb(II) from binary mixtures, retaining >90 % removal efficiency over three cycles due to strong coordination with histidine ligands (Guo et al., 2020).

Notably, the use of SBA in systems treating both organic and inorganic pollutants is gaining traction. Ahmad et al. (2022) demonstrated that Fe-N doped biochar composites derived from biomass not only adsorbed Cr(VI) effectively but also nitrobenzene via π–π stacking and electron transfer mechanisms (Ahmad et al., 2022). These findings reveal the potential of SBA-based materials to act as dual-function adsorbents, paving the way for integrated pollutant management strategies. Such multifunctionality, when combined with low cost and biodegradability, reinforces SBA's role in advanced water treatment processes. In conclusion, the combination of availability, versatility, ease of modification, rapid kinetics, potential for regeneration, and alignment with sustainability goals underscores the strengths of SBA in water treatment applications. Their adaptability and cost-effectiveness make them a promising solution for addressing diverse and complex water pollution issues.

3.2. Weaknesses

Despite the numerous advantages of SBA, several notable weaknesses must be addressed to fully harness their potential in water treatment applications. A primary concern is the inherent variability in SD composition and quality, due to its origin as a wood-derived material. Different wood types, even within the same species, can exhibit differences in lignin, cellulose, and hemicellulose content, all of which influence adsorption behavior (Schubert et al., 2023). This variability alters the physicochemical properties of the resulting adsorbents, leading to changes in surface functionality and adsorption site availability. The problem is further compounded by the diversity of experimental conditions and SD pretreatment methods across studies. For instance, reported Q_m values vary widely: 4.43 to 738.9 mg/g for Pb(II) (Mutiara et al., 2019; Tatu-Qassim et al., 2023), 0.82 to 253.37 mg/g for Cu(II) (Orozco et al., 2023; Zhou et al., 2023), and 0.85 to 241.23 mg/g for Zn (II) (Kovacova, 2019; Tatu-Qassim et al., 2023). Such broad ranges in adsorption capacities arise not only from differences in the target contaminants and testing environments, but also from the lack of standardization in SD sources and processing methods. This variation makes it difficult to draw direct comparisons between studies or establish reliable performance benchmarks. Therefore, it becomes challenging to determine which synthesis parameters consistently lead to high adsorption performance, and this complicates the development of scalable production strategies. Without clear guidelines, it is difficult to ensure that materials prepared under different conditions will perform similarly in real applications.

Another critical weakness is the potential for secondary pollution. While SBA aim to mitigate environmental contamination, they could inadvertently introduce new problems. Many chemical modifications of SD involve acids, alkalis, or organic compounds, which, if not handled properly, could lead to environmental contamination (Housni et al., 2023). Additionally, raw or minimally processed SD may release organic compounds, such as tannins or lignins, into treated water, potentially necessitating additional treatment steps (Vasić et al., 2023). For example, in Cu(II) removal experiments, pH-dependent leaching of organic compounds from SD was observed, particularly when the pH exceeded 7 (Mannaï et al., 2022).

Scaling up laboratory results to industrial applications is another significant challenge. Most studies on SBA focus on small-scale, batch experiments, which allow precise control over experimental variables but do not adequately simulate the operational complexity of real treatment systems. As a result, their performance in large-scale, continuous flow systems remains largely untested. Only a few studies have explored the use of SD in adsorption columns, which are more representative of industrial water treatment processes (Blagojev et al., 2021; Politi and Sidiras, 2020; Qamouche et al., 2021). Adsorption columns differ fundamentally from batch systems, as they require sustained flow, stable pressure, and consistent adsorbent contact time. The complexities associated with continuous operation systems, such as channeling, clogging, and maintaining consistent contact time, could significantly impact the effectiveness of SBA in real-world applications (Loganathan et al., 2022). For example, channeling may reduce contact between the contaminant and the adsorbent surface, while clogging from particulates or biomass buildup may disrupt flow, both leading to a decrease in overall treatment efficiency.

The tendency to oversimplify research and application further limits the understanding and potential of SBA. Many studies focus on single-metal systems under controlled laboratory conditions, which do not accurately reflect the complexity of real-world water contamination scenarios. In practice, water bodies often contain complex mixtures of pollutants and varying environmental conditions (Talukder et al., 2024). Only a few studies have examined the performance of SBA in multi-metal systems or untreated industrial effluents, where competitive adsorption effects can significantly reduce adsorption efficiency (Guo et al., 2020; Kumari et al., 2023; Rani et al., 2022). In mixed-contaminant environments, different metal ions may compete for the same active sites on the SBA surface, leading to reduced uptake for individual metals compared to single-ion systems. This lack of research on more realistic scenarios suggests that the effectiveness of SBA in real-world applications remains largely unverified, and its capacity to perform under complex environmental conditions is still not well understood.

The lack of precision in determining the true equilibrium time for adsorption in some studies poses a significant weakness. While adsorption equilibrium is often reported to occur within 15–60 min (El Hajam et al., 2020; Nurnabi et al., 2020), some studies extend this period to as long as 24 h (Demcak et al., 2019; Kovacova et al., 2020; Mutiara et al., 2019). This variation in reported equilibrium times may not reflect the actual kinetics of the process but rather limitations in sampling frequency or measurement resolution. There is a possibility that equilibrium could be reached much earlier, but the lack of precise, shorter-interval testing leaves this unresolved. Inaccurate estimation of equilibrium time can misrepresent the adsorption rate, which is a critical parameter in designing treatment systems, especially those operating under time constraints. This gap in research methodology raises concerns about the validity of the reported equilibrium times. To gain more accurate insights and enhance the practical applicability of SBA, it is essential to conduct more rigorous testing within shorter time frames. Without this, the true efficiency and potential speed of these adsorbents remain underexplored, hindering their potential integration into fast-paced industrial processes where rapid treatment cycles are essential.

The pH dependency of the adsorption process further complicates the use of SBA. Many studies emphasize the importance of optimizing pH for maximum adsorption efficiency. For instance, Cr(VI) adsorption onto Moroccan Atlas cedar wood SD was found to be optimal at a highly acidic pH of 1 (El Hajam et al., 2023). However, maintaining such extreme pH conditions is often impractical outside laboratory settings, due to safety concerns, corrosiveness of equipment, and the cost of pH adjustment at scale. This pH sensitivity means that the effectiveness of SBA can be significantly compromised in real-world scenarios where pH levels may fluctuate or where maintaining a specific pH is impractical or costly (Sato et al., 2022). Furthermore, water treatment facilities often deal with streams of varying composition and buffering capacity, making tight pH control technically challenging and economically inefficient. This limits the feasibility of applying SBA under typical field conditions.

The need for chemical modification to enhance adsorption capacity, while beneficial in improving performance, introduces additional complexity and cost (Qiu et al., 2022). The use of chemicals for modification, such as acids, alkalis, or organic compounds, may offset the eco-friendly nature of SBA and could introduce environmental concerns (Udokpoh and Nnaji, 2023). For example, while PANI modified coco wood SD demonstrated high adsorption capacities, the chemicals involved in the modification process may raise concerns regarding environmental impact and sustainability (Tatu-Qassim et al., 2023).

A key limitation in current research on SBA is the inconsistent reporting of data regarding regeneration and long-term use. Although some studies demonstrate successful reuse over multiple cycles, many omit this information altogether, making it difficult to assess the true longevity and sustainability of these adsorbents (Bouzid et al., 2024). This lack of comprehensive data on performance across repeated use cycles undermines efforts to evaluate their practical applicability (Gkika et al., 2022).

Another concern is the physical stability of SBA, particularly in flow-through systems. SD particles may be prone to disintegration or compaction under pressure, leading to clogging or channeling in fixed-bed columns (Donskoy, 2023). This could reduce efficiency and increase operational challenges in large-scale water treatment applications. The potential for physical instability highlights the need for further research to improve the robustness and durability of SBA (Alam et al., 2020).

Another weakness lies in the well-known adsorption capacity of adsorbents such as biochar or activated carbon. For example, biochars obtained from brassica straw and astragalus reported capacities of 434.85 (Luo et al., 2021) and 490.18 mg/g (Shang et al., 2019) respectively for Cr(VI) removal, compared to the maximum adsorption capacity observed within the reviewed studies, which was 318.3 mg/g, attained with a SBA. Additionally, carboxylated activated carbon derived from jute stick reported an adsorption capacity of 2079 mg/g for Pb(II) (Aziz et al., 2019), against the 738.9 mg/g obtained with SBA. Furthermore, other types of adsorbents, such as those based on graphene, have also shown higher capacities. A functionalized magnetic graphene oxide reported 353.59 mg/g for Cd(II) adsorption (Einollahi Peer et al., 2018), compared to the 284.1 mg/g attained with SBA. Hence, despite their promising performance, SBA demonstrate lower metal adsorption capacities when compared to other advanced adsorbent materials documented in the literature.

On the same regard, while the reviewed studies presented SBA as low-cost adsorbents due to SD being a wood industry byproduct (Zhou et al., 2023), no techno-economic analyses were provided to demonstrate actual cost advantages compared to other adsorbents in terms of production, regeneration, and disposal. This oversight is significant because even if SBA utilize waste materials, their generally lower adsorption efficiency means larger quantities would be required to reduce pollutants below permissible limits in practical applications (GadelHak et al., 2023). Therefore, comprehensive techno-economic analyses are essential for future SBA studies, as they must account for the entire lifecycle costs including production scaling, operational requirements, regeneration cycles, and waste management to provide a meaningful comparison with conventional adsorbents and establish whether the "low-cost" designation is truly warranted in practical wastewater treatment scenarios.

Lastly, the disposal or management of spent SBA loaded with HMs presents a significant challenge. While the initial use of SD as an adsorbent is environmentally friendly, the resulting HMs-laden waste may require special handling and disposal methods, potentially offsetting some of the environmental benefits (Baskar et al., 2022). Developing safe and cost-effective disposal or recycling methods for spent adsorbents is crucial to ensuring the overall sustainability of SBA water treatment technologies (Loffredo, 2022).

In conclusion, while SBA show promise for HMs removal from aqueous solutions, they also present several significant weaknesses, including variability in performance, long equilibrium times, pH sensitivity, the need for chemical modification, competitive adsorption issues, regeneration challenges, physical instability, and disposal concerns. Addressing these weaknesses through further research and development is essential for realizing the full potential of SBA in water treatment applications.

3.3. Opportunities

The increasing emphasis on circular economy principles presents a significant opportunity for SBA. By transforming waste into a valuable resource for environmental remediation, these materials align with global sustainability goals. Utilizing biowaste such as SD allows companies to enhance their sustainability profiles, making them more attractive to policymakers and industries aiming to reduce their environmental impact (Kainth et al., 2024). This approach is well-aligned with the circular economy, where agricultural and industrial byproducts are recycled into valuable resources, as seen in the successful use of adsorbents for HMs removal (Madeła and Skuza, 2021). Companies could strategically market their adoption of SBA water treatment systems as part of their corporate social responsibility efforts, adding value beyond the direct environmental benefits. This strategy not only supports sustainability goals but also offers a practical solution to the growing challenge of solid waste management (Kumar et al., 2023).

One of the most promising opportunities lies in the valorization of wood industry waste (C. Wang et al., 2020). Research demonstrates that a wide variety of wood types can serve as effective adsorbents, including pine, spruce, oak, beech, and tropical woods like narra and mango. This diversity enables the creation of localized solutions that utilize readily available waste materials, reducing both waste disposal costs and addressing water pollution issues (Jamkar et al., 2023). For instance, regions with robust forestry or furniture manufacturing industries could implement water treatment systems that leverage their specific wood waste, turning a local byproduct into a valuable resource (Younas et al., 2021). This not only enhances the sustainability of local industries but also contributes to the global effort to reduce environmental degradation.

The modifiability of SBA offers substantial opportunities for creating tailored solutions for various industries and contaminants. A wide range of modification techniques, from simple acid or alkali treatments to more sophisticated methods like nanoparticle incorporation and polymer grafting, allows for precise tuning of adsorbent properties such as surface area and chemical reactivity (Mubarak et al., 2024), or providing additional functions. For example, PAMAM-TiO_2 modified oak wood SD demonstrated significant adsorption capacities for HMs, including Cu (II), Pb(II), and Zn(II), while also displaying antimicrobial activity against bacteria and fungi, illustrating its potential as a highly effective, multi-purpose adsorbent (Ibrahim et al., 2022). Coupling SD with magnetic nanoparticles, such as Fe_3O_4, could create adsorbents that are not only highly effective in removing contaminants but are also easily separable from treated water using magnetic fields. This would streamline the recovery process and reduce the need for complex filtration systems (El-Sheikh et al., 2019). Furthermore, advanced nanocomposites incorporating materials like graphene oxide or carbon nanotubes could improve the mechanical strength and adsorption capacity of SBA, making them more robust and efficient under various environmental conditions (Y. Wang et al., 2019) or the incorporation of stimuli-sensitive motifs, which could dynamically adjust pore structures and surface properties, thereby enhancing performance in various adsorption and desorption scenarios (Y. Jiang et al., 2022). Exploring advanced modification techniques aligns with the goal of using sustainable materials in environmental remediation, offering adaptable solutions for complex water contamination issues in regions with limited water treatment systems.

The high adsorption capacities achieved by some modified SD adsorbents, such as the 738.9 mg/g for Pb(II) achieved with HCl and PANI modified coco wood SD, highlight their potential for efficient, space-saving water treatment solutions (Tatu-Qassim et al., 2023). These high-capacity adsorbents could be particularly valuable in urban areas or industrial settings where space is limited, allowing for the treatment of large volumes of water with relatively small amounts of adsorbent material (Karim et al., 2023). The ability to achieve such high adsorption capacities makes SBA a compelling option for industries seeking to maximize the efficiency of their water treatment processes without requiring extensive infrastructure.

SBA are also compatible with existing water treatment infrastructure, presenting opportunities for seamless integration into current systems. Unlike some advanced water treatment technologies that require complete system overhauls, such as electrodialysis or electrocoagulation (Shahedi et al., 2020), SBA could potentially be incorporated into existing filtration or treatment processes as an additional step (Borovik et al., 2020). This ease of integration could facilitate faster adoption and wider implementation of these sustainable solutions, especially in industries or municipalities that are reluctant to invest in entirely new systems (Álvarez-Torrellas et al., 2023).

The increasing demand for effective and sustainable water treatment solutions due to pollution concerns opens opportunities for the commercialization of SBA technologies. As water pollution becomes a growing issue, industries and consumers are seeking environmentally friendly methods to address the presence of HMs and other pollutants in water (A. Saravanan et al., 2021). Modifying SD can enhance its adsorption capacity, making it an attractive option for treating contaminated water in a cost-effective and renewable manner (Ahamad et al., 2024). These factors position SBA as a viable commercial solution for industrial and consumer water treatment needs (Mallakpour et al., 2021).

SBA hold significant promise for industrial applications due to their low cost, renewability, and versatility in treating a range of heavy metal contaminants. Their application could extend beyond small-scale setups to industrial wastewater treatment in sectors such as mining, electroplating, battery manufacturing, and textiles, where metal-laden effluents are a major concern (Shrestha et al., 2021). The relatively simple production processes for many SBA offer opportunities for local manufacturing and job creation. Unlike high-tech water treatment solutions that require specialized facilities, many of the SD modifications described could be implemented in small-scale, local operations, particularly in rural areas or developing regions where centralized infrastructure is lacking (Huang et al., 2021). Wastewater treatment systems utilizing lignocellulosic waste materials like SD have already demonstrated success in such settings, showcasing their cost-effectiveness and ability to treat wastewater (Dabrowska et al., 2022). Additionally, SBA share the sustainability advantages seen in other bio-based materials, such as biochar, making them a fitting solution for decentralized water treatment (Priya et al., 2024).

However, scaling up SBA from lab-scale to industrial deployment presents key challenges. Maintaining consistent quality across production batches is critical, especially given the variability of feedstock sources and potential differences in surface chemistry and adsorption performance. Moreover, few pilot-scale studies exist that validate their performance in continuous-flow systems or under complex, multi-contaminant conditions typical of industrial effluents. The lack of engineered designs tailored to SBA integration into existing treatment infrastructure also hampers broader adoption.

Beyond water treatment, SBA also show potential for removing HMs from soil. For instance, mango wood SD has been tested as a soil additive to analyze HMs bioaccumulation in crops, and it was found that plant bioaccumulation was minimized when grown in soil treated with SD (Kumari et al., 2023). This suggests the possibility of developing integrated environmental remediation solutions that address both water and soil contamination, a significant concern in many industrial and agricultural settings (Ahmed et al., 2022).

The growing field of resource recovery from waste streams presents significant opportunities for SBA. These materials can be engineered to capture and facilitate the recovery of valuable metals, aligning with the goals of closed-loop systems and circular economy strategies (Taghvaie Nakhjiri et al., 2022). For example, PNAH grafted birch wood SD has shown effectiveness in adsorbing gold(III) (Au(III)) and palladium(II) (Pd(II)), in addition to other HMs (Guo et al., 2020). This capability not only reduces environmental impact but also enhances economic benefits by recovering precious metals from waste streams. Integrating SBA into industrial processes supports the circular economy by enabling the recovery of valuable resources, furthering both environmental sustainability and industrial efficiency (Udugama et al., 2020).

In summary, the opportunities for SBA are vast and varied. They range from enhancing sustainability profiles and localizing waste valorization to integrating with nanotechnology and existing infrastructure, all while addressing pressing environmental challenges. As industries and societies continue to prioritize sustainable solutions, SBA are well-positioned to play a significant role in the future of environmental remediation.

3.4. Threats

SBA face considerable competition from well-established water treatment technologies. Conventional methods like ion exchange, reverse osmosis, and activated carbon adsorption are deeply integrated into existing infrastructure, offering proven effectiveness across various industrial and municipal applications (Berneschi et al., 2021; de Mello et al., 2022; Mengesha and Sahu, 2022). The inertia of these established systems creates a significant barrier to the adoption of new technologies, even those that may offer improved sustainability (Roba et al., 2022; Sadjadi and Fernández, 2023). As a result, industries and municipalities may be reluctant to invest in new SBA systems, despite their potential long-term advantages.

Another threat arises from the rapid advancement of alternative green technologies for water treatment. While SBA are promising, other sustainable solutions such as biochar, agricultural waste-based adsorbents, and advanced membrane technologies are also being developed (Hublikar et al., 2024; Younas et al., 2021). For example, a macroalgae-based adsorbent was compared with SBA for the removal of Cu(II) and Zn(II), achieving significantly higher removal rates of 72.37 mg/g for Cu(II) and 52.40 mg/g for Zn(II), compared to the values obtained with SBA of 2.9 mg/g for Cu(II) and 3 mg/g for Zn(II) (Richards et al., 2019). This competitive landscape could overshadow the benefits of SBA, particularly if other materials prove to be more efficient or versatile.

Economic factors present several challenges for SBA implementation. While promising in laboratory settings, the cost-effectiveness of SBA, while promising, is not consistently demonstrated across all studies or at industrial scale. Additional costs associated with chemical modifications, processing, regeneration processes, and waste management need to be carefully evaluated against conventional methods (Malyshkina, 2020). A comprehensive economic assessment must quantify both direct and indirect costs, including energy requirements, chemical consumption, disposal expenses, and potential revenue from recovered metals. Moreover, fluctuations in the availability and price of SD, influenced by changes in the wood industry, increased demand for wood products, or competing uses, could impact the economic feasibility of these adsorbents (Gerandi et al., 2024). The economics of scale present additional challenges: small-scale operations may struggle to justify the initial capital investment required for treatment infrastructure, while larger operations face questions of consistent supply and quality control. As the circular economy gains traction, SD is increasingly being utilized in applications beyond water treatment, such as biofuel production and composite materials (Gupta et al., 2022), potentially limiting availability or driving up costs. Future economic models should incorporate regulatory compliance benefits and potential cost savings from avoiding conventional treatment methods to provide a more accurate assessment of SBA implementation costs versus benefits.

The long-term environmental implications of widespread SBA use require thorough assessment from a sustainability perspective. While utilizing wood industry byproducts aligns with circular economy principles, the life cycle assessment of SBA implementation must evaluate both waste valorization benefits and end-of-life management challenges. Sustainable implementation would require establishing closed-loop systems where recovered metals are returned to production cycles and spent adsorbents are safely repurposed or biodegraded, minimizing waste generation and resource consumption (Kylili et al., 2023). Additionally, widespread adoption of SBA technology could potentially affect forestry management practices and wood processing industries, as demand for specific wood types increases. This raises questions about land use changes, biodiversity impacts, and the overall carbon footprint of SBA production chains.

More specifically, the potential for bioaccumulation of HMs in SBA raises concerns about their environmental impact. While these adsorbents effectively remove HMs from water, the concentrated HMs in the spent adsorbent could pose a risk if not properly managed (Nthwane et al., 2024). Improper disposal of HMs-laden adsorbents can lead to secondary environmental pollution, as these contaminants are not degradable. The potential leaching of adsorbed metals into soil and groundwater presents a significant concern, particularly as climate change may alter precipitation patterns and soil chemistry, potentially affecting the stability of disposed adsorbents (Baskar et al., 2022). Although strategies for regenerating and recycling spent adsorbents are being developed, optimizing these processes for large-scale use remains challenging, and further research is needed to ensure effective metal recovery and minimize environmental impact (Velempini et al., 2023). The energy and chemical inputs required for regeneration processes must be balanced against the environmental benefits of metal recovery and adsorbent reuse to ensure genuine environmental sustainability. On the same regard, the long-term stability and performance of SBA under varied environmental conditions is a significant concern. While some studies have demonstrated successful regeneration and reuse with minimal loss of performance (Orozco et al., 2023; Sinyeue et al., 2022), others have reported efficiency losses exceeding 50 % after multiple cycles, likely due to material degradation over time (Praipipat et al., 2023; Wu et al., 2023). This highlights the need for long-term data on the stability of these materials over extended periods and multiple treatment cycles, which is directly related to their overall environmental sustainability and life-cycle impact.

Regulatory considerations play a critical role in shaping the feasibility of large-scale implementation of SBA for heavy metal HMs removal. On one hand, increasingly stringent water quality standards present a significant opportunity by driving demand for more sustainable and efficient treatment technologies like SBA (Dalcin and Fernandes Marques, 2020). However, these same regulations can also pose substantial barriers. The approval process for integrating new treatment materials into municipal or industrial water systems is often complex and time-consuming, involving extensive performance validation and compliance with strict safety and efficacy benchmarks. This process may be particularly challenging for SBA due to the inherent variability in SD composition, which can affect adsorption performance and reproducibility across different batches and sources (Bieber et al., 2018).

Moreover, the lifecycle management of SBA introduces additional regulatory hurdles. Spent adsorbents saturated with HMs are classified as hazardous waste in many jurisdictions, triggering stringent handling, transport, and disposal requirements (Velempini et al., 2023). The lack of standardized protocols for the safe disposal or regeneration of HMs-laden SBA further complicates their use at scale. Without clear regulatory pathways for end-of-life management, operators may face legal and environmental liabilities, discouraging adoption. Additionally, the absence of consistent certification frameworks tailored to biomass-derived adsorbents may hinder market acceptance and limit funding opportunities for pilot-scale or commercial deployment (Ringenberg et al., 2017). Therefore, addressing these regulatory and institutional challenges is essential for the broader implementation of SBA technologies in real-world water treatment scenarios.

In addition to the challenges discussed above, other emerging threats must also be acknowledged. Intellectual property concerns, such as the formation of dense patent landscapes around specific modification techniques, may hinder innovation and increase the cost of developing and implementing SBA for water treatment applications (Carlaw et al., 2006; Roh et al., 2021; Siri et al., 2020). The current focus on a limited range of modification methods, particularly acid and alkali treatments, may also constrain progress. This emphasis could lead to the neglect of potentially more effective approaches, such as esterification or organosolv treatments, and may leave the field vulnerable to material supply issues (Gajjar et al., 2019). Climate change further contributes to uncertainty by potentially altering forest ecosystems, which could affect the availability and characteristics of SD as a raw material (Miller et al., 2022; Shestakova and Martínez-Sancho, 2021). Public perception may also pose a barrier, especially in the context of drinking water treatment, where the use of waste-derived materials might raise concerns among consumers or regulators despite scientific support for their safety and effectiveness (Morone and Imbert, 2020; Zhou et al., 2023). Additionally, the global nature of the water treatment sector introduces complexity. Variations in water chemistry, pollutant types, and environmental regulations across regions may require extensive local adaptation of SBA technologies, which could limit their widespread applicability. Addressing these diverse threats is essential to support the long-term feasibility and sustainability of SBA deployment.

4. Conclusion and future perspectives

In the comprehensive review of advances in SBA for HMs removal from water, both significant progress and areas requiring further research are highlighted. SBA exhibit strong potential as a water treatment solution, combining low cost, wide availability, and enhanced adsorption capacities, particularly following specific chemical modifications. These modifications range from simple treatments, such as alkaline and acid processes, to biomass functionalization for the development of biocomposites.

Between 2019 and 2024, the advances achieved have evidenced substantial improvements in adsorption capacity, kinetics, and selectivity, positioning SBA as viable alternatives to conventional adsorbents in sustainable water treatment applications.

However, critical limitations persist. The inherent variability in SD composition, the pH sensitivity of the adsorption process, and potential risks of secondary pollution pose significant challenges to the reproducibility, scalability, and environmental sustainability of these technologies. Furthermore, studies addressing adsorbent regeneration, mechanical stability under continuous flow conditions, and the disposal of HM-saturated materials remain insufficient.

Important research gaps require urgent attention, including the development of standardized performance testing protocols, long-term assessments of regeneration and stability, pilot-scale experiments in continuous flow systems, and techno-economic analyses to validate practical applicability. Additionally, the competitive adsorption behavior in multi-component systems under variable environmental conditions remains largely unexplored.

Future research should focus on developing greener and more sustainable modification methods, optimizing the integration of SBA into modular water treatment systems, and conducting field studies and life cycle assessments. It is also crucial to design strategies for the valorization or safe disposal of spent adsorbents. Addressing these challenges will be essential to advance SBA from laboratory success to practical solutions capable of mitigating heavy metal contamination at industrial and environmental scales.

In conclusion, SBA represent a sustainable and viable approach for water treatment, particularly for heavy metal removal, contributing to Sustainable Development Goals 6, 12, and 14, which focus on Clean Water and Sanitation, Responsible Production and Consumption, and Climate Action. SBA offer solutions that simultaneously address waste management and water pollution, promoting the valorization of solid waste and reducing the demand for raw materials. These benefits positively impact water quality, particularly in vulnerable regions where poverty and water scarcity converge.

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CRediT authorship contribution statement

Luis A. Torres-Castañón: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adriana Robledo-Peralta:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christian Antileo:** Validation, Supervision, Formal analysis, Data curation. **Felipe de J. Silerio-Vázquez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **José B. Proal-Nájera:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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