Progress in Agricultural Engineering Sciences 19 (2023) 1, 1–13
DOI: 10.1556/446.2023.00068

AKADÉMIAI KIADÓ

A review of the advancements of potentially toxic element adsorption by various cellulose-based materials and the used adsorbents' fate

HEBA NASER[1*], IMRE CZINKOTA[2], ANDREA DORKOTA[1] and
MÁRK HORVÁTH[1]

[1] Department of Environmental Analysis and Environmental Technology, Institute of Environmental Science, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, 2100, Hungary

[2] Department of Soil, Institute of Environmental Science, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, 2100, Hungary

REVIEW PAPER

Received: June 6, 2023 • Accepted: September 12, 2023

ABSTRACT

In this study, we compile the findings to date on using several cellulose-based materials as adsorbents of potentially toxic elements (PTEs) from wastewater. Furthermore, this review discussed the destiny of PTEs-loaded cellulose-based adsorbents and some sustainable methods for their management, hoping to close the pollution loop.

KEYWORDS

potential toxic elements (PTEs), cellulose, paper, wood mulch, adsorbent fate

---

[*] Corresponding author. Department of Environmental Analysis and Environmental Technology, Institute of Environmental Science, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő 2100. E-mail: haboosh_1983@yahoo.com

INTRODUCTION

Potentially toxic elements (PTEs) are ubiquitous environmental pollutants that significantly threaten human health because they tend to intoxicate, accumulate in, and remain in ecological media (Nguyen et al., 2020) classified potentially toxic elements as hazardous pollutants, especially in aquatic ecosystems. PTEs pollution is a global environmental issue due to the continuous discharge of pollutants from various sources, including industrial effluents, mining activities, agricultural runoff, and improper waste disposal.

Traditional methods for treating wastewater contaminated with PTEs ions include chemical processes (oxidation and reduction, ion exchange filtration, precipitation, and electrochemical treatments) and other physical processes like evaporation treatments (Volesky, 1994; Vievard et al., 2023). However, as stated by Veglio and Beolchini (1997), these high-technology processes have significant drawbacks, such as incomplete metal removal, expensive equipment and monitoring systems, high reagent energy, and the production of toxic sludge or other waste products that need to be disposed of. Therefore, the development of effective and eco-friendly adsorbents for the removal of PTEs is of paramount importance. Therefore, selecting, developing, and characterizing adsorbent materials is critical in designing an adsorption process for water treatment. Adsorbents for water treatment must have the following characteristics: low cost and availability, chemical stability, mechanical stability, good textural and physicochemical properties, high adsorption capacity, high efficiency, fast kinetics, and the ability to regenerate and reuse (Dotto and Mckay, 2020). Many materials, including agriculture products, red mud, clay minerals, fly ash, Portland cement, and cellulose-based materials, have been tested as cheap and abundant adsorbents (Mondal et al., 2019; Nag and Biswas, 2021).

Biological materials, including living and non-living biomaterials, have been widely used to remove pollutants in wastewater, such as PTEs, ions, and dyes (Çolak et al., 2009; Chu and Phang, 2019; Kratochvil and Volesky, 1998). The offered advantages of the biosorption process are the low operating cost, the possibility of regeneration of biosorbents, metal recovery, and the minimization of the quantity of chemical and biological sludge needed to be managed (Kratochvil and Volesky, 1998; Beni and Esmaeili, 2020).

In recent years, cellulose-based adsorbents have attracted much interest as a potentially helpful material for removing PTEs from contaminated water. Cellulose is an attractive material for the adsorption of PTEs due to its unique physicochemical properties, such as its high surface area, biocompatibility, and low cost. Physical and chemical processes, including ion exchange, electrostatic interactions, and complexation, are involved in the adsorption of PTEs onto bio-based adsorbents (Kurniawan et al., 2023). Most cellulose-based adsorbents follow the pseudo-second-order kinetic model, which assumes that the rate-limiting step is chemisorption (Syeda and Yap, 2022). Other researchers modified cellulose-based adsorbents' surface chemistry and morphology through various methods such as chemical modification, physical treatment, and grafting of functional groups to enhance their adsorption capacity and selectivity (de Quadros et al., 2016).

Researchers have investigated the efficacy of many cellulose-based adsorbents in removing PTEs from polluted water. However, the existing data is scattered; a comprehensive study is necessary for discussing the field's past and current advancements. Therefore, this review further discussed some research questions, such as the fate of the cellulose-based adsorbents loaded with PTEs, which is rarely studied in the literature but is a significant concern due to the potential environmental impacts they may cause.

CELLULOSE

Cellulose is nature's most prevalent biopolymer and is the primary component of plant fibers, which provide plant rigidity (Sharma et al., 2019). It is a long-chained linear polysaccharide composed of β-d-glucopyranose units linked by β-1.4 glycosidic linkages (Faruk et al., 2012; Henriksson and Berglund, 2007; O'Connell et al., 2008). Figure 1 shows the chemical structure of cellulose.

Cellulose-based materials have been used in various construction applications, primarily as intact wood. Furthermore, cellulose is abundant in commonly used materials such as cotton (90%), wood (50%), and dried hemp (57%). It has many applications in various fields but is most commonly used in producing paper, cardboard, and derivative products such as cellophane and rayon. It is also a significant component of cotton and linen textiles. In addition, powdered cellulose and microcrystalline cellulose are used in the pharmaceutical industry as inactive drug fillers. Also, cellulose is a versatile starting material for chemical conversions that produce artificial cellulose-based threads and films and several stable cellulose derivatives utilized in various industrial and consumer applications (Gupta et al., 2019).

The cellulose content is variable in agricultural and waste materials; some cellulose content in different materials is presented in Table 1.

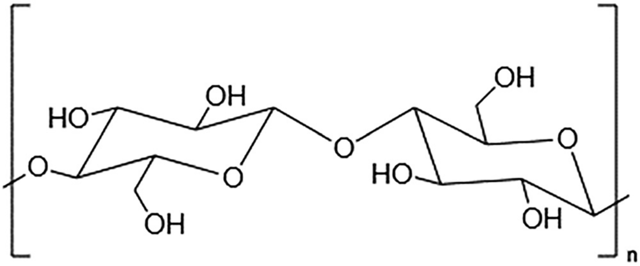

Fig. 1. Chemical structure of cellulose

Table 1. The cellulose content in different materials

Material	Cellulose content (%)	Source
Oakwood	41	Le Floch et al. (2015)
Wastepaper	90–99	Sahin and Arslan (2008)
Cotton	95	Holtzapple (2003)
Leaf fiber	55–73	Hokkanen et al. (2016)
Paulownia wood	43.93	Huo et al. (2022)
Crop residues	30–50	Koul et al. (2022)
Wheat straw	30	Sundarraj and Ranganathan (2018)
Jute fiber	58–63	Wang et al. (2008)
Maize Straw	28–44	Rehman et al. (2014)
Coconut waste	28.7	Rojas et al. (2018)

Several natural cellulose-based materials have been tested by researchers and found promising results for PTEs removal, such as coconut shells (Tan et al., 1993; Low et al., 1995; Baes et al., 1996; Pino et al., 2006); wood sawdust (Sharma and Forster, 1994; Mohan and Singh, 2002; Dakiky et al., 2002; Šćiban and Klašnja, 2003; Acar and Eren, 2006; Gupta and Babu, 2009; Putra et al., 2014), and paper waste as adsorbents for the removal of dyes and PTEs from wastewater (Fahad et al., 2018). These eco-friendly adsorbents show good affinity towards PTEs due to the cellulose content in these materials, which have good adsorption potential due to O-containing and hydroxyl functional groups (Jamshaid et al., 2017). Surface complexation, ion exchange, and electrostatic contact were all mentioned as adsorption methods by which these functional groups may efficiently coordinate with PTEs (Han et al., 2022). Binding affinity is greatly affected by whether PTE ions establish bonds with monodentate or bidentate functional groups (Zhang et al., 2020). In addition, PTEs' charge and valency affect the interface's electrical characteristics. Metal ions with positive charges, such as Cd (II), Pb (II), and Hg (II), have an electrostatic attraction towards functional groups with a negative charge. Arsenate ($AsO_4{}^{3-}$) ions, which are negatively charged, prefer to attach to positively charged sites. According to Han et al. (2022), the electrostatic interactions between PTE ions and functional groups are enhanced for divalent and trivalent PTE ions compared to monovalent PTE ions due to the valency effect.

Most adsorption studies were conducted using untreated cellulosic materials, and only a few demonstrated good adsorption potential. Other researchers applied physical and chemical treatment, which significantly impacted the performance of these adsorbents. For example, Šoštarić et al. (2018) applied treatment with NaOH to apricot shells, increasing the adsorption capacity by 90%, 154%, and 61% for $Pb^{2+,}$ Cu^{2+}, and Zn^{2+}, respectively. Wang et al. (2019) developed a carboxymethylated cellulose fiber for water purification. The prepared carboxymethylated cellulose fiber bio-adsorbent removed Cu (II) more effectively than the unmodified fibers, whose adsorption capacity increased 130-fold. In another study, Huo et al. (2022) used a wood-based adsorbent modified by esterification with phosphoric acid. The ideal adsorption conditions were 318.15 K with pH = 6, and the phosphorylated wood maximum adsorption capacity was 130.2 mg g^{-1}, seven times higher than that of the alkaline extracted wood (18.5 mg g^{-1}).

The most recent studies are concentrated on synthesizing cellulose- and nano-cellulose-based adsorbents. For example, maleic acid-modified nano-cellulose has a greater maximum adsorption capacity for Pb^{2+} (115 mg g^{-1}) than maleic acid-modified macro (20 mg g^{-1}), according to Vadakkekara et al. (2019). Furthermore, Hamad et al. (2020) prepared a hybrid nanofibers composite adsorbent membrane of modified cellulose nanofibers with modified hydroxyapatite for the removal of both lead (Pb) and ferrous (Fe) ions from simulated wastewater; the results demonstrated that this composite offers a higher adsorption capacity than either material alone. To achieve removal efficiencies of 99.7 and 95.47% for Pb (II) and Fe (III), respectively, the optimal conditions for the adsorption efficiency of Pb (II) and Fe (III) ions in wastewater were at the equilibrium time of 35 and 40 min, respectively, at pH = 6, room temperature, 0.1 gm of adsorbent, V = 50 ml. Moreover, in a comparison study Sirviö and Ivanka (2020) compared the adsorption capacity of lignin-rich wood nanofibers and cellulose nanofibers produced from bleached cellulose fibers for lead and copper adsorption. Nanofibers of bleached cellulose pulp showed a lower adsorption capacity of copper and lead compared to lignin-rich nanofibers.

PTES ADSORPTION BY PAPER

The globe generates more than 300 million tons of paper annually, and demand is expected to double before 2030. Papers and cardboards account for 40% of municipal solid waste (Putro et al., 2019). Paper waste for PTEs adsorption has gained significant attention recently due to its low cost, high availability, and eco-friendliness. Several types of paper waste have been investigated for their adsorption properties, including recycled paper, newsprint, cardboard, and office paper. The properties of the paper waste, such as its surface area, pore size distribution, and chemical composition, significantly impact its adsorption capacity.

Recent studies have demonstrated the potential of paper waste as an adsorbent for PTEs. For instance, waste printing paper exhibited a high adsorption efficiency of 90% and metal uptake of less than 25 mg g^{-1} for evaluated metal ions (Moyib et al., 2017). Extraction of micro-fibrillated cellulose from wastepaper using simple sulfonation resulted in a 250% increase in adsorption capacity for lead (Pb) ions compared to pristine micro-fibrillated cellulose (Sridhar and Park, 2020).

In a study conducted by Chakravarty et al. (2008), newspaper pulp was used as an adsorbent for removing copper from effluent. The study found that the newspaper pulp adsorbent removed copper effectively, with a maximal loading capacity of 30 mg g^{-1} at an initial Cu concentration of 20 mg L^{-1}. The study also found that the adsorption of Cu onto the newspaper is a physisorption spontaneous endothermic process. Not only but also modified newspaper pulp with citric acid was used as an adsorbent: Pitsari et al. (2013) investigated the modification by 0.5 M and 1 M citric acid to improve lead adsorption, which increased adsorption capacity by 35% and 82%, respectively.

Additionally, paper sludge waste, a by-product of the paper industry, has been explored for PTEs adsorption. Adsorbents derived from de-inking paper sludge showed higher removal of Cu^{2+} than virgin pulp mill sludge (Méndez et al., 2009).

Several researchers have investigated the use of modified paper residue for the adsorption of potentially toxic elements. Using paper functionalized with polyethyleneimine (Setyono and Valiyaveettil, 2016) successfully removed nanoparticles, $Ni^{2+,}$ $Cd^{2+,}$ and Cu^{2+} cations, and Cr (VI) anions from polluted water samples. Coated polyethyleneimine paper demonstrated significantly higher adsorption capacities for the pollutants examined in this study compared to untreated paper; these capacities were observed for PTEs Ni^{2+} (208 mg g^{-1}), Cd^{2+}(370 mg g^{-1}), and Cu^{2+} (435 mg g^{-1}) ions compared to nanoparticles (17–79 mg g^{-1}), and Cr (VI) (64 mg g^{-1}) anions.

Finally, the factors that affect the adsorption of PTEs onto paper waste have been extensively investigated, including the pH of the solution (Fawzy and Gomaa, 2020), the initial concentration of the pollutant, the contact time (Dehghani et al., 2016), and the temperature. Further research is needed to optimize paper waste's adsorption performance and explore its potential for large-scale applications.

PTES ADSORPTION BY WOOD MULCH AND SAWDUST

Mulch is a protective covering of material laid on top of the soil. Because of its low cost and simple availability, ground, shredded, or chipped wood is the most popular product in the mulch industry. In addition, mulching provides soil erosion prevention, moisture conservation, and weed control (Soleimanifar et al., 2019). The quantitative examination of oak wood macromolecule content yielded data from many authors; according to Puech (1978), Kollmann and Fengel (1965), Herrera et al. (2014), the proportions of cellulose, hemicellulose, and lignin were 41%, 26.35%, and 25.71%, respectively.

Sawdust is a powdery by-product of woodworking processes such as sawing and milling. It can sorb PTEs in stormwater (Deng, 2020). Wood mulch and sawdust are effective adsorbents for various pollutants, including potentially toxic elements (PTEs). This review discusses some of the studies that have investigated the adsorption of PTEs by wood mulch and sawdust.

Different types of wood mulch have been investigated as adsorbents of PTEs from wastewater; in a study by (Jang et al., 2005), three types of mulch were used as sorbents to collect PTEs in urban runoff. The results revealed that hardwood bark mulch has the optimum physicochemical features for heavy metal ion adsorption. When the Hardwood mulch dosage was $4\,\mathrm{g\,L^{-1}}$, and the pH was less than 6, more than 90% of the Pb (II) in the solution could be eliminated. Nevertheless, the required hardwood mulch dosage was more than $6\,\mathrm{g\,L^{-1}}$, achieving better than 80% removal efficiency for Cu (II) and Zn (II). When the adsorption capabilities at pH 6.0 and 5.0 are compared, a slight variation indicates that the pH is unimportant.

In another study of hardwood adsorption of several contaminants by Ray et al. (2006), the results showed that chromium (Cr^{6+}), Copper (Cu^{2+}), cadmium (Cd^{2+})’ zinc (Zn^{2+}), lead (Pb^{2+}), fluoranthene, naphthalene, butyl benzyl phthalate, 1,3dichlorobenzene, and benzo(a) pyrene were all sorbed by hardwood mulch from a spiked stormwater pollutant sorbed mass depending on pollutant species, contact time, and initial concentration.

Furthermore, Iqbal et al. (2020) proved that mulches are an excellent source for removing PTEs from soil solutions, and the results showed that utilizing woodchips and compost in forest regions can create complexes with copper metal and transform it into a form that is not hazardous for crop plant growth.

Sawdust as an adsorbent of PTEs was studied by (Šćiban et al., 2007); the study focused on the efficiency of potential toxic elements removal by using sawdust with different quantities (1.25, 2.5, 3.75, 5, 10 and $20\,\mathrm{g\,L^{-1)}}$, the most significant removal efficiencies for Cu (II), Zn (II), and Cd (II) were 76.2, 37.5, and 31.9%, respectively.

Recently modifications on wood mulch and sawdust adsorbents were applied by different researchers; for example, the biosorption ability of natural and modified poplar, cherry, spruce, and hornbeam sawdust in removing PTEs from acidic model solutions was investigated by Kovacova et al. (2020): they studied the efficiency of alkaline modified sawdust for metal removal from model solutions at varying beginning concentrations of Cu (II) and Zn (II). Poplar treated by KOH had the maximum adsorption efficiency values for zinc (98.2% at pH 7.3) and copper (94.3% at pH 6.8). Sidhu et al. (2021) investigated other modifications, including using iron-based water treatment residuals coated wood mulch to reduce common contaminants in urban runoff. The results reveal that the unique adsorption media removed more Cu, Pb, Zn, and P than the typical uncoated mulch. Coated wood mulches were synthesized and evaluated in another study for removing PTEs and phosphorus (P) from synthetic urban stormwater (Soleimanifar et al., 2016). In batch experiments, the composite adsorption capacity was 97% lead (Pb), 76% zinc (Zn), 81% copper (Cu), and 97% phosphorus (P) for the tested synthetic stormwater (containing $\mathrm{Pb} = 100\,\mathrm{g\,L^{-1}}$, $\mathrm{Zn} = 800\,\mathrm{g\,L^{-1}}$, $\mathrm{Cu} = 100\,\mathrm{g\,L^{-1}}$, $P = 2.30\,\mathrm{mg\,L^{-1}}$) at $\mathrm{pH} = 7.0$.

Other reviewed modifications by Meez et al. (2021) of sawdust as an adsorbent material to enhance its selectivity and capacity involved various modifying agents, including (I) organic compounds (ethylene diamine, formaldehyde, epichlorohydrin, methanol, dyes); (ii) acid solutions (HCl, H_2SO_4, H_3PO_4, CH_3COOH, HNO_3, citric acid); (iii) mineral salts (NaCl, KCl, $NaHCO_4$); (iv) basic solutions (NaOH, $Ca(OH)_2$, KOH, Na_2CO_3); (v) phosphorylation treatment ($CO(NH_2)_2$ (urea) + H_3PO_4).

THE FATE OF USED CELLULOSE-BASED ADSORBENTS

Cellulose-based adsorbents are widely used in various applications such as water treatment, environmental remediation, and removing heavy metals and dyes from wastewater. However, the fate of these adsorbents after their use has become a significant concern due to the potential environmental impacts they may cause.

Incineration is a frequent way of disposing of used cellulose-based adsorbents. Unfortunately, this process can release harmful air pollutants like volatile PTEs (Xiong et al., 2019). Furthermore, the ash created by burning cellulose-based adsorbents may contain PTEs that are hazardous to human health and the environment. It causes secondary pollution through PTEs leaching into groundwater.

Another technique for getting rid of used cellulose-based adsorbents is landfilling. Unfortunately, the adsorbents can release hazardous chemicals into the soil and water nearby, endangering the environment. There may be issues with toxins seeping into groundwater since, in most situations, the contaminated cellulose-based adsorbent will contain high water content inappropriate for landfilling (Hubbe, 2022). In addition, the degradation of cellulose-based adsorbents in landfills can contribute to the creation of greenhouse gases, mainly methane, significantly contributing to climate change.

Scientists have investigated several techniques for reusing and recycling cellulose-based adsorbents to address these challenges, several researchers recycled the adsorbents using desorption techniques like heat or chemical treatment. This avenue of research was notably investigated by Liu et al. (2002), who tested the adsorption and desorption of Copper (II) using a spherical cellulose adsorbent. An aqueous solution of NaOH or HCl can be used to recover the Cu^{2+} ions that have been adsorbed on the adsorbent. The maximum recovery rate is nearly 100% using a 2.4 mol L^{-1} HCl solution. Moreover, the adsorption capacity was lowered after 30 cycles of adsorption/desorption by only 7.2%. Therefore, the need for new adsorbents can be reduced, and waste can be reduced by reusing previously used adsorbents in various applications. For instance, the regeneration of adsorbents using the eutectic freeze crystallization process was explored by Hubbe et al. (2018).

Another strategy is to repurpose used cellulose-based adsorbents as value-added products. Adsorbents, for example, can be pyrolyzed to form biochar, which can be utilized as a soil amendment or a renewable energy source and for further adsorption processes. Agarwal et al. (2015) investigated the removal of azo dye using biochar from pyrolysis of cellulose-based materials municipal solid waste. Table 2 summarizes some PTEs cellulose-based adsorbents, and their treatment methods reported in the literature.

Finally, the fate of used cellulose-based adsorbents is a critical issue that requires careful consideration. Further research is essential to develop more efficient and sustainable methods for managing used adsorbents.

Table 2. Potentially toxic elements cellulose-based adsorbents and their treatment methods

Potentially toxic elements	Adsorbent	Treatment	Reference
Ni, Zn, Cd	Residues of pine sawdust, sunflower seed hulls, and corn residues mix	Immobilization of used adsorbents in clay ceramics	Simón et al. (2022)
Pb, Ni	Paper sludge waste	Sulfur treatment with K_2S solution	Wajima (2013)
Cu	Grape bagasse	Pyrolysis	da Silva et al. (2022)
Zn, Ni, Cu, Co, Cd	Succinic anhydride-modified mercerized nanocellulose	Regeneration	Hokkanen et al. (2013)
Cr	Pine sawdust and oak wood ash	Regeneration	Núñez-Delgado et al. (2015)
Cd, Zn, Pb, Cu	Paper and Mulch adsorbents waste	Incineration and Immobilization of adsorbent ash into mortar	Naser et al. (2023)

ACKNOWLEDGMENTS

The research was supported by the project 'Preparation for the transition to circular economy in the case of agricultural and green waste' of Environment and Energy Efficiency Operational Programme grant scheme of the Ministry of Technology and Industry Hungary under grant no.: KEHOP-3.2.1-15-2021-00037.

REFERENCES

Acar, F.N. and Eren, Z. (2006). Removal of Cu (II) ions by activated poplar sawdust (Samsun Clone) from aqueous solutions. *Journal of Hazardous Materials*, 137(2): 909–914.

Agarwal, M., Tardio, J., and Mohan, S.V. (2015). Pyrolysis biochar from cellulosic municipal solid waste as adsorbent for azo dye removal: equilibrium isotherms and kinetics analysis. *International Journal of Environmental Science and Development*, 6(1): 67.

Baes, A.U., Umali, S.J.P., and Mercado, R.L. (1996). Ion exchange and adsorption of some heavy metals in a modified coconut coir cation exchanger. *Water Science and Technology*, 34(11): 193–200.

Beni, A.A. and Esmaeili, A. (2020). Biosorption, an efficient method for removing heavy metals from industrial effluents: a review. *Environmental Technology & Innovation*, 17: 100503.

Chakravarty, S., Pimple, S., Chaturvedi, H.T., Singh, S., and Gupta, K.K. (2008). Removal of copper from aqueous solution using newspaper pulp as an adsorbent. *Journal of Hazardous Materials*, 159(2–3): 396–403.

Chu, W.L. and Phang, S.M. (2019). Biosorption of heavy metals and dyes from industrial effluents by microalgae. In: Alam, M. and Wang, Z. (Eds.), *Microalgae biotechnology for development of biofuel and wastewater treatment*, pp. 599–634. https://doi.org/10.1007/978-981-13-2264-8_23.

Çolak, F., Atar, N., and Olgun, A. (2009). Biosorption of acidic dyes from aqueous solution by Paenibacillus macerans: kinetic, thermodynamic and equilibrium studies. *Chemical Engineering Journal*, 150(1): 122–130.

da Silva, C.M., da Boit Martinello, K., Lütke, S.F., Godinho, M., Perondi, D., Silva, L.F., and Dotto, G.L. (2022). *Pyrolysis of grape bagasse to produce char for Cu (II) adsorption: a circular economy perspective*. Biomass Conversion and Borefinery, pp. 1–18.

Dakiky, M., Khamis, M., Manassra, A., and Mer'Eb, M. (2002). Selective adsorption of chromium (VI) in industrial wastewater using low-cost abundantly available adsorbents. *Advances in Environmental Research*, 6(4): 533–540.

de Quadros Melo, D., de Oliveira Sousa Neto, V., de Freitas Barros, F.C., Raulino, G.S.C., Vidal, C.B., and do Nascimento, R.F. (2016). Chemical modifications of lignocellulosic materials and their application for removal of cations and anions from aqueous solutions. *Journal of Applied Polymer Science*, 133(15).

Dehghani, M.H., Sanaei, D., Ali, I., and Bhatnagar, A. (2016). Removal of chromium (VI) from aqueous solution using treated waste newspaper as a low-cost adsorbent: kinetic modeling and isotherm studies. *Journal of Molecular Liquids*, 215: 671–679.

Deng, Y. (2020). Low-cost adsorbents for urban stormwater pollution control. *Frontiers of Environmental Science & Engineering*, 14: 1–8.

Dotto, G. and McKay, G. (2020). Current scenario and challenges in adsorption for water treatment. *Journal of Environmental Chemical Engineering*, 8(4), art. no. 103988.

Fahad, B.M., Ali, N.S., and Hameed, T.T. (2018). Using paper waste as adsorbent for methyl violet dye removal from wastewater. *Journal of Engineering and Sustainable Development*, 22(1): 1–11.

Faruk, O., Bledzki, A.K., Fink, H.P., and Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000-2010. *Progress in Polymer Science*, 37(11): 1552–1596. https://doi.org/10.1016/j.progpolymsci.2012.04.003.

Fawzy, M.A. and Gomaa, M. (2020). Use of algal biorefinery waste and waste office paper in the development of xerogels: a low cost and eco-friendly biosorbent for the effective removal of Congo red and Fe (II) from aqueous solutions. *Journal of Environmental Management*, 262: 110380.

Gupta, P.K., Raghunath, S.S., Prasanna, D.V., Venkat, P., Shree, V., Chithananthan, C., Choudhary, S., Surender, K., and Geetha, K. (2019). An update on overview of cellulose, its structure and applications. In: Pascual, A.R. and Martín, M.E.E. (Eds.), *Cellulose*. IntechOpen. https://doi.org/10.5772/intechopen.84727.

Gupta, S. and Babu, B.V. (2009). Removal of toxic metal Cr (VI) from aqueous solutions using sawdust as adsorbent: equilibrium, kinetics and regeneration studies. *Chemical Engineering Journal*, 150(2–3): 352–365.

Hamad, A.A., Hassouna, M.S., Shalaby, T.I., Elkady, M.F., Abd Elkawi, M.A., and Hamad, H.A. (2020). Electrospun cellulose acetate nanofiber incorporated with hydroxyapatite for removal of heavy metals. *International Journal of Biological Macromolecules*, 151: 1299–1313.

Han, B., Weatherley, A.J., Mumford, K., Bolan, N., He, J.Z., Stevens, G.W., and Chen, D. (2022). Modification of naturally abundant resources for remediation of potentially toxic elements: a review. *Journal of Hazardous Materials*, 421: 126755.

Henriksson, M. and Berglund, L.A. (2007). Structure and properties of cellulose nanocomposite films containing melamine formaldehyde. *Journal of Applied Polymer Science*, 106(4): 2817–2824. https://doi.org/10.1002/app.26946.

Herrera, R., Erdocia, X., Llano-Ponte, R., and Labidi, J. (2014). Characterization of hydrothermally treated wood in relation to changes on its chemical composition and physical properties. *Journal of analytical and Applied Pyrolysis*, 107: 256–266.

Hokkanen, S., Bhatnagar, A., and Sillanpää, M. (2016). A review on modification methods to cellulose-based adsorbents to improve adsorption capacity. *Water Research*, 91: 156–173.

Hokkanen, S., Repo, E., and Sillanpää, M. (2013). Removal of heavy metals from aqueous solutions by succinic anhydride modified mercerized nanocellulose. *Chemical Engineering Journal*, 223: 40–47.

Holtzapple, M.T. (2003). *Cellulose*. Elsevier EBooks, pp. 998–1007. https://doi.org/10.1016/b0-12-227055-x/00185-1.

Hubbe, M.A. (2022). What to do with toxic, contaminated cellulose-based adsorbents. *BioResources*, 17(1): 3–6. https://doi.org/10.15376/biores.17.1.3-6.

Hubbe, M.A., Becheleni, E.M.A., Lewis, A.E., Peters, E.M., Gan, W., Nong, G., Mandal, S., and Shi, S.Q. (2018). Recovery of inorganic compounds from spent alkaline pulping liquor by eutectic freeze crystallization and supporting unit operations: a Review. *BioResources*, 13(4): 9180–9219.

Huo, H., Yu, Y., Zhang, X., Tang, M., Chen, C., Wang, S., and Min, D. (2022). Phosphorylated wood designed as a biosorbent for effectively removing Ni2+ from wastewater. *Industrial Crops and Products*, 188: 115727.

Iqbal, R., Raza, M.A.S., Valipour, M., Saleem, M.F., Zaheer, M.S., Ahmad, S., Toleikiene, M., Haider, I., Aslam, U.M., and Nazar, M.A. (2020). Potential agricultural and environmental benefits of mulches—a review. *Bulletin of the National Research Centre*, 44(1): 1–16.

Jamshaid, A., Hamid, A., Muhammad, N., Naseer, A., Ghauri, M., Iqbal, J., Rafiq, S., and Shah, N.S. (2017). Cellulose-based materials for the removal of heavy metals from wastewater–an overview. *ChemBioEng Reviews*, 4(4): 240–256. https://doi.org/10.1002/cben.201700002.

Jang, A., Seo, Y., and Bishop, P.L. (2005). The removal of heavy metals in urban runoff by sorption on mulch. *Environmental Pollution*, 133(1): 117–127.

Kollmann, F. and Fengel, D. (1965). Changes in the chemical composition of wood by thermal treatment. *Holz als Roh-und Werkstoff*, 23: 461–468.

Koul, B., Yakoob, M., and Shah, M.P. (2022). Agricultural waste management strategies for environmental sustainability. *Environmental Research*, 206: 112285.

Kovacova, Z., Demcak, S., Balintova, M., Pla, C., and Zinicovscaia, I. (2020). Influence of wooden sawdust treatments on Cu (II) and Zn (II) removal from water. *Materials*, 13(16): 3575.

Kratochvil, D. and Volesky, B. (1998). Advances in the biosorption of heavy metals. *Trends in Biotechnology*, 16(7): 291–300.

Kurniawan, T.A., Lo, W.H., Liang, X., Goh, H.H., Othman, M.H.D., Chong, K.K., Mohyuddin, A., Kern, A.O., and Chew, K.W. (2023). Heavy metal removal from aqueous solutions using biomaterials and/or functional composites: recent advances and the way forward in wastewater treatment using digitalization. *Journal of Composites Science*, 7(2): 84.

Le Floch, A., Jourdes, M., and Teissedre, P.L. (2015). Polysaccharides and lignin from oak wood used in cooperage: composition, interest, assays: a review. *Carbohydrate Research*, 417: 94–102.

Liu, M., Deng, Y., Zhan, H., and Zhang, X. (2002). Adsorption and desorption of copper (II) from solutions on new spherical cellulose adsorbent. *Journal of Applied Polymer Science*, 84(3): 478–485.

Low, K.S., Lee, C.K., and Wong, S.L. (1995). Effect of dye modification on the sorption of copper by coconut husk. *Environmental Technology*, 16(9): 877–883.

Meez, E., Rahdar, A., and Kyzas, G.Z. (2021). Sawdust for the removal of heavy metals from water: a review. *Molecules*, 26(14): 4318.

Méndez, A., Barriga, S., Fidalgo, J.M., and Gascó, G. (2009). Adsorbent materials from paper industry waste materials and their use in Cu (II) removal from water. *Journal of Hazardous Materials*, 165(1–3): 736–743.

Mohan, D. and Singh, K.P. (2002). Single- and multi-component adsorption of cadmium and zinc using activated carbon derived from bagasse—an agricultural waste. *Water Research*, 36(9): 2304–2318.

Mondal, M., Manoli, K., and Ray, A. (2019). Removal of arsenic(III) from aqueous solution by concrete-based adsorbents. *The Canadian Journal of Chemical Engineering*, 98(1): 353–359.

Moyib, O.K., Ayedun, M.A., Awokoya, O.J., and Omotola, O.E. (2017). Waste printing paper as analogous adsorbents for PTEs in aqueous solution. *Nigerian Journal of Chemical Research*, 22(1): 29–38.

Nag, S. and Biswas, S. (2021). Cellulose-based adsorbents for heavy metal removal. In: Inamuddin, Ahamed, M., Lichtfouse, E., and Asiri, A. (Eds.), *Green adsorbents to remove metals, dyes and boron from polluted water. Environmental chemistry for a sustainable world*, Vol. 49. Springer, Cham. https://doi.org/10.1007/978-3-030-47400-3_5.

Naser, H., Horváth, M., and Czinkota, I. (2023). Incorporation of adsorbent ash with potentially toxic elements into mortar: a sustainable approach. *Journal of Hazardous, Toxic, and Radioactive Waste*, 27(1): 04022037.

Nguyen, B.T., Do, D.D., Nguyen, T.X., Nguyen, V.N., Nguyen, D.T.P., Nguyen, M.H., Truong, H.T.T., Dong, H.P, Le, A.H., Bach, Q.V., and Bach, Q.V. (2020). Seasonal, spatial variation, and pollution sources of heavy metals in the sediment of the Saigon River, Vietnam. *Environmental Pollution*, 256: 113412.

Núñez-Delgado, A., Fernández-Sanjurjo, M.J., Álvarez-Rodríguez, E., Cutillas-Barreiro, L., Nóvoa-Muñoz, J., and Arias-Estévez, M. (2015). Cr (VI) sorption/desorption on pine sawdust and oak wood ash. *International Journal of Environmental Research and Public Health*, 12(8): 8849–8860.

O'Connell, D.W., Birkinshaw, C., and O'Dwyer, T., F. (2008). Heavy metal adsorbents prepared from the modification of cellulose: a review. *Bioresource Technology*, 99: 6709–6724. https://doi.org/10.1016/j.biortech.2008.01.036.

Pino, G.H., De Mesquita, L.M.S., Torem, M.L., and Pinto, G.A.S. (2006). Biosorption of cadmium by green coconut shell powder. *Minerals Engineering*, 19(5): 380–387.

Pitsari, S., Tsoufakis, E., and Loizidou, M. (2013). Enhanced lead adsorption by unbleached newspaper pulp modified with citric acid. *Chemical Engineering Journal*, 223: 18–30.

Puech, J.L. (1978). Substances phenoliques des eaux-de-vie d'armagnac. III. Sur la presence des ethoxyles dans la lignine d'extraction et les produits de sa degradation. *Industries Alimentaires et Agricoles*, 95(1): 13–22.

Putra, W.P., Kamari, A., Yusoff, S.N.M., Ishak, C.F., Mohamed, A., Hashim, N., and Isa, I.M. (2014). Biosorption of Cu (II), Pb (II) and Zn (II) ions from aqueous solutions using selected waste materials: adsorption and characterisation studies. *Journal of Encapsulation and Adsorption Sciences*, 2014.

Putro, J.N., Santoso, S.P., Soetaredjo, F.E., Ismadji, S., and Ju, Y.H. (2019). Nanocrystalline cellulose from waste paper: adsorbent for azo dyes removal. *Environmental Nanotechnology, Monitoring & Management*, 12: 100260.

Ray, A.B., Selvakumar, A., and Tafuri, A.N. (2006). Removal of selected pollutants from aqueous media by hardwood mulch. *Journal of Hazardous Materials*, 136(2): 213–218.

Rehman, N., de Miranda, M.I.G., Rosa, S.M., Pimentel, D.M., Nachtigall, S.M., and Bica, C.I. (2014). Cellulose and nanocellulose from maize straw: an insight on the crystal properties. *Journal of Polymers and the Environment*, 22(2): 252–259.

Rojas-Valencia, M.N., Galeana-Olvera, E., Fernández-Rojas, D.Y., Mendoza-Buenrostro, C., Nájera-Aguilar, H.A., and Vaca-Mier, M. (2018). Isolation of cellulose nanofibrils from coconut waste for the production of sewing thread. *Advanced Materials Science*, 3(1): 1–3.

Sahin, H.T. and Arslan, M.B. (2008). A study on physical and chemical properties of cellulose paper immersed in various solvent mixtures. *International Journal of Molecular Sciences*, 9(1): 78–88.

Šćiban, M. and Klašnja, M. (2003). Optimization on of usage of wood sawdust adsorbent of heavy metal ions from water. *International Symposium Interdisciplinary Regional Research*, 3: 51–56.

Šćiban, M., Radetić, B., Kevrešan, Ž., and Klašnja, M. (2007). Adsorption of heavy metals from electroplating wastewater by wood sawdust. *Bioresource Technology*, 98(2): 402–409.

Setyono, D. and Valiyaveettil, S. (2016). Functionalized paper—a readily accessible adsorbent for removal of dissolved heavy metal salts and nanoparticles from water. *Journal of Hazardous Materials*, 302: 120–128.

Sharma, A., Thakur, M., Bhattacharya, M., Mandal, T., and Goswami, S. (2019). Commercial application of cellulose nano-composites–A review. *Biotechnology Reports*, 21: e00316.

Sharma, D.C. and Forster, C.F. (1994). A preliminary examination into the adsorption of hexavalent chromium using low-cost adsorbents. *Bioresource Technology*, 47(3): 257–264.

Sidhu, V., Barrett, K., Park, D.Y., Deng, Y., Datta, R., and Sarkar, D. (2021). Wood mulch coated with iron-based water treatment residuals for the abatement of metals and phosphorus in simulated stormwater runoff. *Environmental Technology & Innovation*, 21: 101214.

Simón, D., Palet, C., Costas, A., and Cristóbal, A. (2022). Agro-industrial waste as potential heavy metal adsorbents and subsequent safe disposal of spent adsorbents. *Water*, 14(20): 3298.

Sirviö, J.A. and Visanko, M. (2020). Lignin-rich sulfated wood nanofibers as high-performing adsorbents for the removal of lead and copper from water. *Journal of Hazardous Materials*, 383: 121174.

Soleimanifar, H., Deng, Y., Barrett, K., Feng, H., Li, X., and Sarkar, D. (2019). Water treatment residual-coated wood mulch for addressing urban stormwater pollution. *Water Environment Research*, 91(6): 523–535.

Soleimanifar, H., Deng, Y., Wu, L., and Sarkar, D. (2016). Water treatment residual (WTR)-coated wood mulch for alleviation of toxic metals and phosphorus from polluted urban stormwater runoff. *Chemosphere*, 154: 289–292.

Šoštarić, T.D., Petrović, M.S., Pastor, F.T., Lončarević, D.R., Petrović, J.T., Milojković, J.V., and Stojanović, M.D. (2018). Study of heavy metals biosorption on native and alkali-treated apricot shells and its application in wastewater treatment. *Journal of Molecular Liquids*, 259: 340–349.

Sridhar, V. and Park, H. (2020). Extraction of microfibrillar cellulose from wastepaper by NaOH/urethane aqueous system and its utility in removal of lead from contaminated water. *Materials*, 13(12): 2850.

Sundarraj, A.A. and Ranganathan, T.V. (2018). A review on cellulose and its utilization from agro-industrial waste. *Drug Invention Today*, 10(1): 89–94.

Syeda, H.I. and Yap, P.S. (2022). A review on three-dimensional cellulose-based aerogels for the removal of heavy metals from water. *Science of the Total Environment*, 807: 150606.

Tan, W.T., Ooi, S.T., and Lee, C.K. (1993). Removal of chromium (VI) from solution by coconut husk and palm pressed fibres. *Environmental Technology*, 14(3): 277–282.

Vadakkekara, G.J., Thomas, S., and Nair, C.R. (2019). Maleic acid modified cellulose for scavenging lead from water. *International Journal of Biological Macromolecules*, 129: 293–304.

Veglio, F. and Beolchini, F. (1997). Removal of metals by biosorption: a review. *Hydrometallurgy*, 44: 301–316.

Vievard, J., Alem, A., Pantet, A., Ahfir, N.D., Arellano-Sánchez, M.G., Devouge-Boyer, C., and Mignot, M. (2023). Bio-based adsorption as ecofriendly method for wastewater decontamination: a review. *Toxics*, 11(5): 404.

Volesky, B. (1994). Advances in biosorption of metals: selection of biomass types. *FEMS Microbiology Reviews*, 14(4): 291–302.

Wajima, T. (2013). Conversion of waste paper sludge into heavy metal adsorbent using sulfur impregnation. *Advanced Materials Research*, 699: 759–764.

Wang, J., Liu, M., Duan, C., Sun, J., and Xu, Y. (2019). Preparation and characterization of cellulose-based adsorbent and its application in heavy metal ions removal. *Carbohydrate Polymers*, 206: 837–843.

Wang, W.M., Cai, Z.S., and Yu, J.Y. (2008). Study on the chemical modification process of jute fiber. *Journal of Engineered Fibers and Fabrics*, 3(2): 155892500800300203.

Xiong, X., Liu, X., Iris, K.M., Wang, L., Zhou, J., Sun, X., Rinklebe, J., Shaheen, S.M., Ok, Y.S., Lin, Z., and Tsang, D.C.W. (2019). Potentially toxic elements in solid waste streams: fate and management approaches. *Environmental Pollution*, 253: 680–707.

Zhang, H., Xu, F., Xue, J., Chen, S., Wang, J., and Yang, Y. (2020). Enhanced removal of heavy metal ions from aqueous solution using manganese dioxide-loaded biochar: behaviour and mechanism. *Scientific Reports*, 10(1): 1–13.