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Review

Adsorbents for the removal of arsenic, cadmium, and lead from contaminated waters

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ABSTRACT

The removal of cadmium, arsenic, and lead from drinking and irrigation water is a recurring challenge, especially in developing countries. Cost considerations can make it expedient to use local materials, produced in agricultural or industrial operations, as adsorbents for these toxins. Performance of these materials may not always be optimal, but their immediate availability often makes them attractive choices. This review presents a compilation of adsorption techniques, many of which are based on the use of low-value products.

Contents

1. Introduction

Environmental toxins entering the food chain through drinking water and crop irrigation are a widespread problem, especially in poorer countries. Cadmium, arsenic, and lead (CAL) stand out among these poisons, because of their toxicity and ubiquity [1–12]. Removing CAL from large volumes of water can be technically challenging and expensive, putting it beyond the means of many developing nations, as well as local authorities in other parts of the world. These problems can sometimes be alleviated through the use of adsorbent materials that are available locally or regionally, dispensing with the need for costly transport.

A wealth of information is available on materials with adsorbent qualities that are available in certain localities but do not have the intrinsic worth to warrant transport over long distances. Many of these materials are of natural origin, such as crop residues, plant products, or geological deposits. Others may be byproducts of industrial processes that are normally considered waste. In some instances they are usable as-is, in others they may require some form of modification or pretreatment.

The aim of this report is to present a broad view of adsorbents that have been identified for use in CAL removal from waters. A variety of materials have been surveyed, with emphasis on those that are inexpensive and available at various locations around the world. While CAL were the toxins selected for this compilation, the adsorbents in question are often applicable to other (mostly cationic) species as well. In many cases the references themselves may provide this additional information, while in other cases it may lead the reader to further experimentation. The information, which is supplied without critical comment, is organized in Tables 1–5, including lists of parameters based on those generally reported in the literature. Not all publications consulted for this report provided the same suite of parameters, and in many cases they were presented in different ways and formats. This is also true for the units used: the most widely encountered ones are quoted in the column headings of the tables, but in instances where authors opted for a different unit it is retained and shown with the entry in question.

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Table 1
Summary of adsorbents.

Arsenic(III)	References	Arsenic(V)	References	Cadmium	References	Lead	References
$Al_2O_3/Fe(OH)_3$	[13]	$Al_2O_3/Fe(OH)_3$	[13]	*Alcaligenes eutrophus*	[14]	Adsorbents, agricultural	[15]
Alumina, activated	[16]	Alginate bead with iron	[17]	Algae, marine, dead biomass	[18]	Algae, marine, dead biomass	[19]
Alumina, iron hydroxide coated	[20]	Alumina, activated	[21–23]	Algae, Nile water	[24]	Alginate beads	[25]
Bauxsol, activated	[26,27]	Alumina, iron hydroxide coated	[20]	Alginate carriers	[28]	Apricot stone	[29]
Biomass	[30]	Bauxite, calcined	[31]	Aluminosilicates	[32]	Ash, brick kiln	[33]
Cactaceous powder	[34]	Bauxsol	[35]	Aluminum electrodes	[36]	*Azolla filiculoides*	[37]
Carbon, char	[38]	Bauxsol-coated sand	[35]	Anthracite	[39]	Bacteria, sulfate reducing	[40]
Carbon, coconut husk	[41]	Bauxsol, activated	[26,27]	Aragonite shells	[42]	Bagasse fly ash (1998)	[43]
Cellulose (bead) with iron oxyhydroxide	[44]	Biomass, yeast, methylated	[45]	*Ascophyllum nodosum*	[46]	Bagasse fly ash (2004)	[47]
Cement, iron oxide coated	[48]	Carbon, activated	[49]	*Aspergillus niger*, live	[50]	Bed sediments	[51]
Cement, Portland	[52]	Carbon, char	[38]	*Bacillus subtilis* cell walls	[53]	Biomass of *Spirulina maxima*	[54]
Char, oak bark	[55]	Carbon, coal based	[38]	Bagasse fly ash	[56]	Biomass, filamentous fungi	[57]
Char, oak wood	[55]	Carbon, coconut shell	[58]	Bark, pine	[39]	Biomass, *Mucor rouxil*, dead	[59]
Char, pine bark	[55]	Carbon, peat-based	[49]	*Bifurcaria bifurcata*	[46]	Biomass, *Mucor rouxil*, live	[59]
Char, pine wood	[55]	Cellulose (bead) with iron oxyhydroxide	[44]	Biofilm	[60]	Biomass, *Pinus sylvestris* cone	[61]
Fe–Mn binary oxide	[62,63]	Cement, iron oxide coated	[48]	Biofilter	[64]	Biosurfactant	[65]
Fe–Mn mineral material	[66]	Cement, Portland	[52]	Biomass, sargassum waste	[67]	Bone powder	[68]
$FePO_4$ (amorphous)	[69]	Chitosan	[70]	Calcite	[71]	Carbon, activated	[68]
$FePO_4$ (cryst.)	[69]	Coconut coir pith	[72]	*Candida utilis*	[73]	Carbon, commercial	[68]
Ferric hydroxide, granular	[74]	Fe–Mn binary oxide	[62,63]	Carbon, activated, biofilm covered	[60]	Carbonate hydroxyapatite	[75]
Ferriginous manganese ore	[76]	Fe–Mn mineral material	[66]	Carbon, biological activated	[64]	Ceramics	[68]
Gibbsite	[77]	Feldspar	[78]	Carbon, F-400 active	[79]	Cereal chaff	[80]
Goethite	[62,77]	$FePO_4$ (amorphous)	[69]	Carbon, granular activated, with biofilm	[60]	Charcoal, natural	[81]
Hematite	[21,82]	$FePO_4$ (crystalline)	[69]	Carbonaceous material, natural	[39]	Chitin, natural	[83]
Hybrid (polymer/inorganic)	[84]	Ferrihydrite	[85]	Caustic magnesia	[86]	Chitin, phosphorylated	[83]
Iron(III)-loaded chelating resin	[87]	Ferruginous manganese ore	[76]	Charcoal, coconut shell, activated	[88]	Chitin, xanthated	[83]
Kaolinite, surfactant modified	[89]	Gibbsite	[77]	*Cladosporium resinae*	[90]	Chitins, surface modified	[83]
Lamarack seed powder	[91]	Goethite	[62,77]	Clay, mixed	[92]	*Chlorella vulgaris* cells, dead	[25]
Laterite soil	[93]	Hematite	[94,95]	Coal, bituminous	[39]	*Chlorella vulgaris* cells, live	[25]
MnO_2	[96]	Human hair	[97]	Cobalt–nickel solutions	[98]	Clinoptilolite, natural	[99]
Orange juice residue	[100]	Hybrid (polymer/inorganic)	[84]	Coke	[39]	Cocoa shells	[101]
Orange waste, phosphorylated	[102]	Hydrotalcite	[103]	Cork	[39]	Coconut	[104]
Oxisol	[77]	Hydrotalcite, synthetic	[105]	Fly ash, bagasse	[106]	Compost, leaf	[107]
Plant biomass, fresh and immobilized	[108]	Iron(III)-loaded chelating resin	[87]	Fly ash, treated	[109]	Duolite C – 433	[110]
Red earth	[111]	Kaolinite	[77]	*Fucus spiralis*	[112]	Egg shells	[33]
Red mud	[21,112]	Kaolinite, surfactant modified	[89]	Fusinite	[39]	Ferrihydrite	[107]
Sand, iron oxide-coated	[113]	Lamarak seed powder	[91]	Gills of goldfish *Carassius auratus*	[114]	Fish scale, Atlantic cod	[115]
Sea nodules, polymetallic	[116]	Laterite soil	[93]	Granular activated carbon	[64]	Fly ash, bagasse	[117]
Siderite	[94,95]	Layered double hydroxides, calcined	[118]	Inorganic ligands in surfactant solution	[119]	Fly ash, modified, activated	[120]
Slag, iron(III) oxide-loaded	[121]	*Mesorporous silica* media compared with alumina, activated	[122]	Iron electrodes	[123]	Green algae (*Spirogyra* species)	[124]
Sponge, Fe loaded	[125]	MnO_2	[96]	Juniper fiber	[126]	Iron material, recycled	[127]
TiO_2	[128,129]	Orange juice residue	[100]	Kaolinite	[130]	Leaves, *Casurina glauca* tree	[131]
Volcanic stone	[132]	Orange waste, phosphorylated	[102]	*Laminaria ochroleuca*	[46]	Maize cobs	[133]
Zeolite, surfactant modified	[89,134]	Oxisol	[77]	*Lathyrus sativus* husk	[135]	Okra waste	[136]
Zeolites	[132]	Pisolite, activated	[137]	Leaves, *Platanus orientalis*	[138]	Palmyra palm fruit seed carbon	[139]

Table 1 (*Continued*)

Arsenic(III)	References	Arsenic(V)	References	Cadmium	References	Lead	References
Zirconium oxide, monoclinic hydrous	[140]	Rare earth oxide, mixed	[141]	Leonardite	[39]	Peach stone	[29]
Zr resin	[142]	Red earth	[111]	Lignite	[39]	Pedogenic oxides SMS-1 SMS-2	[107]
Zr(IV)-loaded chelating resin	[143]	Red mud	[21,144]	Macroalgae, brown marine	[46]	*Phaseolus vulgaris* L.	[145]
		Red mud, neutralized	[146]	Manganese dioxide	[147]	Phosphate, activated	[148]
		Sand, sulfate-modified, iron oxide-coated	[149]	Membrane, hollow fiber	[150]	Phosphate, natural	[148]
		Sea nodules, polymetallic	[116]	$Multisorb_{TM}$ 100	[39]	Plant powder	[68]
		Siderite	[94,95]	Nanotubes	[151]	*Plantago major* L.	[145]
		Slag, iron(III) oxide-loaded	[121]	Nickel, leaching residue from production	[152]	*Pseudomonas aeruginosa* PU21 beads	[153]
		Soil, Olivier	[154]	Olive stones	[155]	Red mud	[156]
		Soil, Sharkey	[154]	*Paecilomyces variotii*	[90]	Red soil	[157]
		Sponge, Fe loaded	[125]	Peat	[39]	Rice husk	[133]
		TiO_2	[128,129]	*Pelvetia caniculata*	[46]	Sago waste	[158]
		Volcanic stone	[132]	Perlite	[159]	Sand, River Ravi	[33]
		Zeolite, surfactant modified	[89,134]	Pine cone, ground	[160]	Sawdust	[161]
		Zeolites	[132]	Protein, immobilized metallothionein	[162]	Seaweed, brown	[163]
		Zirconium oxide, monoclinic hydrous	[140]	Pumice sand columns	[164]	Seed hull	[104]
		Zirconium-loaded activated carbon	[74]	Red mud	[165]	Sepiolite, natural	[130]
		Zirconium(IV)-loaded chelating resin	[143]	*Rhodobacter sphaeroides*	[166]	Silicate MCM-41, mesoporous	[167]
		Zirconium(IV)-loaded phosphoric chelate adsorbent	[168]	Rhodovulum	[166]	Slag, granular	[169]
		Zr resin	[142]	*Saccorhiza polyschides*	[46]	Soil, fine loamy	[170]
		Zr(IV)-loaded phosphoric acid chelating resin	[171]	Silica, mesoporous	[172]	*Staphylococcus saprophyticus*	[173]
				Silicate MCM-41, mesoporous	[167]	Sugar beet pectin gels	[174]
				Soil, biosolid amended	[175]	Tea waste	[33]
				Soil, Cane	[176]	Vegetable biomass	[177]
				Soil, Fox	[176]	Zeolite tuff	[178]
				Soil, Guelph	[176]	Zeolites, Amasya	[179]
				Soil, Haldimand Ah	[176]		
				Soil, Haldimand Ap	[176]		
				Soil, Hanbury	[176]		
				Soil, Welland	[176]		
				Soils, Ontario	[176]		
				Soybean plants	[180]		
				Tea waste	[181]		
				Thiobacillus ferrooxidans	[182]		
				Water hyacinth	[183]		
				Wood, spruce	[39]		
				Yeast, baker's	[184]		
				Zeolite, synthetic pellets	[185]		
				Zeolites, naturally modified and synthetic	[186]		

Table 2
Removal of arsenic(III).

Adsorbent	Method/type of water	Uptake capacity (mg/g)	Optimum temperature (°C)	Removal (%)	Optimum pH	Sorption energy (kJ/mol)	Sorbent dose (g/L)	Particle diameter (µm)	Contaminant concentration (mg/L)	Contact time	References
$Al_2O_3/Fe(OH)_3$	Batch	0.12 mmol/g	450	92	6.1 ± 0.3		0.1–25 g/100 mL	500–100	0.1–0.4	4 h	[13]
Alumina, activated	Batch/column drinking water	0.180	25	96.2	7.6	0.0082	13	2000–100	20–100	5 h	[16]
Alumina, iron hydroxide coated	Drinking water	7.64	25		6.62–6.74				0.1–1.8 mmol/L		[20]
Bauxsol, activated	Water	0.541	23 ± 1		4.5		5		2.04–156.7 µM		[26,27]
Biomass		13.17	28		2.0				1–10		[30]
Biomass, immobilized	Ground water	704.1	30		6.0				50–2500		[106]
Cactaceous powder	Batch	0.0018			5		250 µg/L	420		24 h	[34]
Carbon, char	Aqueous solution	89.0	25		2–3				193–992		[38]
Carbon, coconut husk	Industrial waster water	146.30	30		12				50–600		[41]
Cellulose (bead) with iron oxyhydroxide	Groundwater	33.2	25 ± 0.5		7.0				1–100 mmol/L		[44]
Cement, iron oxide coated	Drinking water	0.67	35		7				0.7–13.5		[48]
Cement, Portland	Batch/column	3.98	30 ± 2	90	4–5		15	4880–4920	1.99	8 h	[52]
Char, oak bark	Drinking water	0.0074	25		3.5				10–100		[55]
Char, oak wood	Drinking water	0.006	25		35				10–100		[55]
Char, pine bark	Drinking water	12	25		3.5				10–100		[55]
Char, pine wood	Drinking water	0.0012	25		3.5				10–100		[55]
Fe–Mn binary oxide	Batch	1.77 mmol/g	25 ± 1	>96	4.8	187 L/mmol	0.2	26	0.20 mmol/L	24 h	[62,63]
Fe–Mn mineral material	Batch/column	14.7	25 ± 0.5		3		100–1000 mg/L	<38 µm to 0.5 mm	0.47 mmol/L	24 h	[66]
$FePO_4$ (amorphous)	Drinking water	21	20		7–9				0.5–100		[69]
$FePO_4$ (cryst.)	Drinking water	16	20		7–9				0.5–100		[69]
Ferric hydroxide, granular	Column drinking water	2.3	25		8–9				5–100		[74]
Ferriginous manganese ore	Batch	0.5367	25	72.58	2–8	139.05	0.2 g	250–75	12 mg/L	5 min	[76]
Gibbsite	Wastewater	3.30	25		5.5				10–1000		[77]
Goethite	Batch wastewater	7.50	25		5.5				10–1000		[62,77]
Hematite	Wastewater	0.197	30	100	4.2				133.49 µmol/L		[21,82]
Hybrid (polymer/inorganic)	Drinking water	75.67	20		7.7						[84]
Iron(III)-loaded chelating resin	Aqueous solution	62.93	25		9.0						[87]
Kaolinite, surfactant modified	Batch/column	4.3 mmol/kg	22	70	7–9	0.8 L/mmol	0.2	400–1400	0.2–14	24 h	[89]

Lamarack seed powder	Batch	1.50		60.21	7.5	0.04 L/mg	2.0	105–420	25	60 min	[91]
Laterite soil	Batch	1.384	25 ± 2	98	5.7 ± 2	28.267 L/mg	10	164	0.5	4 h	[93]
MnO_2	Batch	0.7 mmol/g		53 mg/g	4.3–3.9		1.6	8	60	2 h	[96]
Orange juice residue	Wastewater	70.43	30		7–11						[100]
Orange waste, phosphorylated	Batch/column	143.25	Room temperature	60	10		0.015	208	15	24 h	[102]
Oxisol	Wastewater	2.60	25		5.5				10–1000		[77]
Plant biomass, fresh and immobilized	Batch/column	128.10, 704.11	29 ± 2	90, 100	6	0.011, 0.008 L/mg	5, 40	1000	100	30, 60 min	[108]
Red earth	Batch	0.308 mM	25		5.5	15.4275 kmol/m^3	5	<63	10–5 M	24 h	[111]
Red mud	Batch	0.884	25	37.3	7.25	0.025 μ/mol	20	<53	33.37–400.4 μmol/L	60 min	[21,111]
Sand, iron oxide-coated	Drinking water	0.14	50		7.2				0.5–3.5		[113]
Sea nodules, polymetallic	Batch	0.74	100–900	90	5.9–6.1		0.02	75	0.34	30 min	[116]
Siderite	Batch and column	1040 μg/g	20 ± 2	458 μg/g		0.0019 L/μg	2	100–250	250–2000	72–194 h	[92,93]
Slag, iron(III) oxide-loaded	Wastewater	2.9–30.1	20		2.5				20–300		[121]
Sponge, Fe loaded	Batch	0.24 ± 0.02 mmol/g	75		9.075	650 ± 30 L/mol	100–3000 mg/L			24 h	[125]
TiO_2	Batch	32.4		95	8.5	1.33×10^{-4} L/μg	0–30	600–150	0.4–80	5 h	[128,129]
Volcanic stone	Batch	0.0018			5		250 μg/L	420		24 h	[132]
Zeolite, surfactant modified	Batch/column	1.6 mmol/kg	22	>75	7.2–7.5	0.8 L/mmol	0.0002	400–1400	0.2–14	24 h	[89,134]
Zeolites	Batch	0.017	22	75	4				0.1–4.0	24 h	[132]
Zirconium oxide, monoclinic hydrous	Drinking water	112.4	25		9–10				1×10^{-3}		[140]
Zr resin	Drinking water	79.42	25		8.0				0–5 mmol/L		[142]
Zr(IV)-loaded chelating resin	Spring water	49.15	25		9.0						[143]

Table 3
Removal of arsenic(V).

Adsorbent	Method/type of water	Uptake capacity (mg/g)	Optimum temperature (°C)	Removal (%)	Optimum pH	Sorption energy (kJ/mol)	Sorbent dose (g/L)	Particle diameter (μm)	Contaminant concentration (mg/L)	Contact time	References
$Al_2O_3/Fe(OH)_3$	Batch	36.7	450	92	8.0 ± 0.3		0.1–2.5 g/100 mL	500–100	0.1–0.4 mmol/L	4 h	[13]
Alginate bead with iron	Column drinking water	0.014	25		7.0				50 μg/L		[17]
Alumina, activated	Batch, column aqueous solution	11.02	32		4.0		10 mg/mL	3.5 nm	20–100	5 h	[21–23]
Alumina, iron hydroxide coated	Drinking water	36.64	25		7.15–7.2				0.1–1.8 mmol/L		[20]
Bauxite, calcined	Ground water	1.57	25		7.0				0.5–8.0		[31]
Bauxsol		1.081	23 ± 1		4.5		5		0.80–32.00 μmol/L		[35]
Bauxsol-coated sand		3.32	25		4.5				0.54–20.34 mg/L		[35]
Bauxsol, activated	Water	7.642	23 ± 1		4.5		5		2.04–156.7 μmol/L		[26,27]
Biomass, yeast, methylated	Surface and ground water	3.75	30		6.5				0.5–2.5 mM		[45]
Carbon, activated	Drinking water	3.08	24		5.0				25–200 μg/L		[49]
Carbon, char	Aqueous solution	34.46	25		2–3				157–737		[38]
Carbon, coal based		4.09	25		5.0				0–200		[38]
Carbon, coconut shell	Wastewater	2.4	25		5.0				0–200		[58]
Carbon, peat-based		4.9	25		5				0–200		[49]
Cellulose (bead) with iron oxyhydroxide	Ground water	33.2	25 ± 0.5		7.0				1–100 mmol/L		[44]
Cement, iron oxide coated	Drinking water	6.43	35		7				0.5–10.0		[48]
Cement, Portland	Batch and column	3.98	30 ± 2	95	5		15	4880–4920	1.99	8 h	[52]
Chitosan	Wastewater	58	25		4.0				400		[70]
Coconut coir pith	Ground water/industrial effluents	13.57	20		7.0				5.0–100 mg/L		[72]
Fe–Mn binary oxide	Batch	0.93 mmol/g	25 ± 1		4.8	6777 L/mmol	0.2	26	0.20 mmol/L	24 h	[62,63]
Fe–Mn mineral material	Batch/column	6.7	25 ± 0.5		3, 5.5		100–1000 mg/L	<38 μm– 0.5 mm	0.01	24 h	[66]
Feldspar	Water/wastewater	0.18	30		4.2				133.49 μmol/L		[78]
$FePO_4$ (amorphous)	Drinking water	10	20		6–6.7				0.5–100		[68]
$FePO_4$ (crystalline)	Drinking water	9	20		6–6.7				0.5–100		[68]
Ferrihydrite	Batch/natural	0.25					0.02–0.09 g/100 mL		325 μg/L	5 h	[86]
Ferruginous manganese ore	Batch	15.38		72.16	2–8	0.9519	0.2 g	250–75	0.19 mg/L	5 min	[73]
Gibbsite	Wastewater	4.60	25		5.5				10–1000		[77]
Goethite	Batch	12.5	25		5.5				10–1000		[62,77]
Hematite	Batch/column wastewater	0.20	30	100	4.2			250–500	133.49 μmol/L	24 h	[94,95]
Human hair	Drinking water	0.012	22						90–360 μg/L		[97]
Hybrid (polymer/inorganic)	Drinking water	81.66	20		7.7						[82]
Hydrotalcite		105	25		7			0.89, 0.77, 0.78 nm	400	18 h	[103]
Hydrotalcite, synthetic	Ground water	105	25		7.0				400		[105]
Iron(III)-loaded chelating resin	Aqueous solution	55.44	25		3.5						[85]
Kaolinite	Wastewater	<0.23	25		5.5				10–1000		[77]
Kaolinite, surfactant modified	Batch/column	9.0 mmol/kg	22	70	5.0–6.5	17 L/mmol	0.2	400–1400	0.2–14	24 h	[87]

Lamarak seed powder	Batch	2.14		85.60	2.5	0.09 L/mg	2.0	105–420	25	60 min	[89]
Laterite soil	Batch	0.04	25 ± 2	95	6.96	48.54 L/mg	20	164	0.5	4 h	[91]
Layered double hydroxides, calcined	Wastewater	5.61	25		4.2–5.4				20–200		[118]
Mesoporous silica media	Drinking water	8.99	25		6.5				0.133–1.33 mmol/L		[122]
MnO_2	Batch	0.3 mmol/g		22 mg/g	4.3–3.9		1.6	8	60	2 h	[96]
Orange juice residue	Wastewater	67.43	30		2–6						[99]
Orange waste, phosphorylated	Batch/column	143.25	Room temperature	99	3		0.015	208	15	18 h	[100]
Oxisol	Wastewater	3.20	25		5.5				10–1000		[79]
Pisolite, activated	River water	3.17	25		6.5				50		[137]
Rare earth oxide, mixed	Wastewater	2.95	29		6.5				50		[141]
Red earth	Batch	0.173 mM	25		5.5	0.2978 kmol/m^2	5	< 63	10–4 M	24 h	[111]
Red mud	Batch	0.941	25	70	3.5	0.123 µ/mol	20	<53	33.37–400.4 µmol/L	48 h	[21,144]
Red mud, neutralized	Tap water	1.081	30		7.3		5		0.80–32.00 Mm		[146]
Sand, sulfate-modified, iron oxide-coated	Drinking water	0.13	27		4–10				0.5–3.5		[149]
Sea nodules, polymetallic	Batch	0.74	100–900	90	2.0–2.2		0.04	75	0.78	30 min	[116]
Siderite	Batch/column	516 µg/g	20 ± 2	386 µg/g	7	0.0066 L/µg	2	100–250	250–2000 µg/L	72–194 h	[94,95]
Slag, iron(III) oxide-loaded	Wastewater	18.8–78.5	20		2.5				20–300		[121]
Soil, Olivier	Soil	0.42	25		5–6				5–100		[154]
Soil, Sharkey	Soil	0.74	25		5–6				5–100		[154]
Sponge, Fe loaded	Batch	1.83 ± 0.04 mmol/g	75		4.5	180 ± 9 L/mol	100–1000 mg/L		100–1000 mg/L	24 h	[125]
TiO_2	Batch/column	41.4		99	7.3	6.59×10^{-5} L/µg	0–30	600–150	20–100	2 h	[128,129]
Volcanic stone	Batch				5			420		24 h	[132]
Zeolite, surfactant modified	Batch/column	7.2 mmol/kg	22	75	7.2–7.5	20 L/mmol	0.0002	400–1400	0.2	24 h	[89,134]
Zeolites	Batch	0.1	22		4				0.1–4.0	24 h	[132]
Zirconium oxide, monoclinic hydrous	Drinking water	89.90	25		4–6				1×10^{-3}		[140]
Zirconium-loaded activated carbon	Column drinking water	2.8	25		8–9				5–100		[165]
Zirconium(IV)-loaded chelating resin	Spring water	88.73	25		4.0						[143]
Zirconium(IV)-loaded phosphoric chelate adsorbent	Column	149.9	25		2.0				5 Mm		[168]
Zr resin	Drinking water	53.94	25		4.5				0–5 mmol/L		[142]
Zr(IV)-loaded phosphoric acid chelating resin	Sea water	49.0			1.14				2.5 mmol/L		[171]

Table 4
Removal of cadmium.

Adsorbent	Method/type of water	Uptake capacity (mg/g)	Optimum temperature (°C)	Removal (%)	Optimum pH	Sorption energy (L/mg)	Sorbent dose (g/L)	Particle diameter (μm)	Contaminant concentration (mg/L)	Equilibrium/ contact time	References
Alcaligenes eutrophus		122		99	7			100			[14]
Algae, marine, dead biomass	Batch	80	25	90	5			0.5–1 mm	2.5 mmol/L	3 h	[18]
Algae, Nile water	Batch	333 μmol/gm	25 ± 2	46	4		2	0.5–1	4–44	2 h	[24]
Alginate Carriers		220 mg		78	2.2				40 g/L	45 min	[28]
Aluminosilicates		0.76–1.03 meq/g	Room temperature		8			8–10 mesh		20 h	[32]
Aluminum electrodes	Electro-coagulation			99.994	10				500 mg/g	60 min	[36]
Anthracite		2			10–11				180	71 h	[39]
Aragonite shells	Batch		25 ± 0.1	99.9	8.2		2	0.3	0.5 μM	72 h	[42]
Ascophyllum nodosum		38		> 90	4.5 ± 0.1			0.45	10	<1 h	[46]
Aspergillus niger, living		15.50	25–30		4				75	24 h	[50]
Bacillus subtilis cell walls					3.4– 7.8						[53]
Bagasse fly ash	Batch	1.20	30–50	90	6.0	7.18	10	200–250	14	60 min	[56]
Bark, pine		5							120	71 h	[39]
Bifurcaria bifurcata				>90	4.5 ± 0.1			0.45		<1 h	[46]
Biofilm	Batch/column	0.8823			7			12–20 mesh	2.25		[60]
Biofilter	Batch/column	0.5	24		8			12–20 mesh	1.9	1.5 h	[64]
Biomass, sargassum waste	Batch		30	100	4.5		0.4	0.56–0.85 mm	0.01	6 h	[67]
Calcite	Batch	18.52	25	99.8	5–6	0.029	0.1	100 mesh	150– 2500 μg/mL	10 min	[71]
Candida utilis			25	≥ 80	6.5		5		5–100		[73]
Carbon, activated, biofilm covered											[60]
Carbon, biological activated	Batch/column	0.6	24		8			12–20 mesh	2.25		[60]
Carbon, F-400 active					10–11					71 h	[79]
Carbon, granular activated, with biofilm	Batch/column	0.6878	24	81	8			12–20 mesh	1.75		[58]
Carbonaceous material, natural											[39]
Caustic magnesia					10			4–0.5	20		[86]
Charcoal, coconut shell, activated	Batch	0.0277	40	640.27	6		5			80 min	[88]
Cladosporium resinae	Batch/column			69.9	6		0.5		50 mg/L	24 h	[90]
Clay, mixed				85	6 –9						[92]
Coal, bituminous		1							180	71 h	[39]
Cobalt–nickel solutions			60		3		0.018			5 min	[98]
Coke		3			10–11				100	71 h	[39]
Cork		6							80	71 h	[39]
Fly ash, bagasse	Batch	2.00	50	99.9	6	7.14	10	100–150	14	60 min	[106]
Fly ash, treated	Batch	14.33	25	99.87	5	0.585	>1.25	<63	1–10	30 min	[109]
Fucus spiralis		64 ± 2	25 ± 0.1	76.6	6.5	0.053	10	0.5–1 mm	10	<1 h	[112]
Fusinite		5.3							80	71 h	[39]
Gills of goldfish *Carassius auratus*									0.100	5 days	[114]
Granular activated carbon	Batch/column	0.2	24		8			12–20 mesh	3.4	4 h	[60]
Inorganic ligands in surfactant solution	Batch			95	7.5		1.0		0.336– 0.286 mol/L	24 h	[119]
Iron electrodes	Electro-coagulation			99.996	10				500	60	[123]

Juniper fiber	Batch	29.5	25		4.2	0.01 L/g	1	0.18 mm	10	1 day	[126]
Kaolinite				98	10				133.33 μM		[130]
Laminaria ochroleuca				> 90	4.5 ± 0.1			0.45		<1 h	[46]
Lathyrus sativus husk	Batch	35	30	95	5		1		10–500		[135]
Leaves, *Platanus orientalis*	Batch	110	24	99	7	0.0495	2 mg/g	0.20– 0.3 mm	2 mg/g	3 h	[138]
Leonardite		5.5							120	71 h	[39]
Lignite		5							65	71 h	[39]
Macroalgae, brown marine											[46]
Manganese dioxide			23 ± 2	87	7.6				50		[147]
Membrane, hollow fiber				95	4			0.03	100 mg/L		[150]
Multisorb$_{TM}$ 100		10							40	71 h	[39]
Nanotubes		11.0			5.5		0.05		4		[151]
Nickel, leaching residue from production		25	22 ± 1		7.2		2		20–4400	24 h	[152]
Olive stones		2.606	80	98	11	8.44 kJ/mol	0.5	0.250– 0.355	10	120 min	[155]
Paecilomyces variotii	Batch/column			79.5	4–5		0.5		10 mg/L	24 h	[90]
Peat		5							40	71 h	[39]
Pelvetia caniculata				>90	4.5 ± 0.1			0.45		<1 h	[46]
Perlite	Batch		22 ± 1	55	6					6 h	[159]
Pine cone, ground		13.56	20				1–4	0.125 mm	200	6–7 h	[160]
Protein, immobilized metallothionein		3.55	298 K	70	5.2				1 mM		[162]
Pumice sand columns	Batch/column	20	20 ± 1	99	7			0.6–2 mm	22	13 days	[164]
Red mud	Batch/column	1.16 mol/g	30	60–65	40	85.9	10	150–200		8–10 h	[165]
Rhodobacter sphaeroides				93.3					5	7 days	[166]
Rhodovulum				95.5					5	7 days	[166]
Saccorhiza polyschides		95		> 90	4.5 ± 0.1			0.45		<1 h	[46]
Silica, mesoporous	Batch	0.99 ± 0.03 mmol/g	25		6		0.2		0–0.027 mM	30 min	[173]
Silicate MCM-41, mesoporous				100	6.7			3.12 nm		24 h	[167]
Soil, biosolid amended			22 ± 1		6.5					48 h	[175]
Soil, Cane	Batch	59.50			5.05						[176]
Soil, Fox	Batch	17.0			7.84						[176]
Soil, Guelph	Batch	46.7			7.79						[176]
Soil, Haldimand Ah	Batch	99.9			8.18						[176]
Soil, Haldimand Ap	Batch	98.0			8.34						[176]
Soil, Hanbury	Batch	84.3			7.57						[176]
Soil, Welland	Batch	49.9			7.4						[176]
Soils, Ontario	Batch		25					2 mm		24 h	[176]
Soybean plants				>90					0.05 μM	30 min	[180]
Tea waste				77.2			0.5 –1.5		5		[181]
Thiobacillus ferrooxidans	Batch		22 ± 2	80	2.5				15 g/L	2–5 d	[182]
Water hyacinth		2044 mg/kg							4	8 days	[183]
Wood, spruce		2							140	71 h	[39]
Yeast, baker's		91.74			6.5		1.0		100		[184]
Zeolite, synthetic pellets	Batch/column	3.14		98	4					1500 min	[185]
Zeolites, naturally modified and synthetic	Batch							0.25–0.315 mm			[186]

Table 5
Removal of lead.

Adsorbent	Method/type of water	Uptake capacity (mg/g)	Optimum temperature (°C)	Removal (%)	Optimum pH	Sorption energy (kJ/mol)	Sorbent dose (g/L)	Particle diameter (μm)	Contaminant concentration (mg/L)	Equilibrium/ contact time	References
Adsorbents, agricultural			28	45	6.2		0.5	106	50	120	[15]
Algae, marine, nonliving biomass	Batch	126.5	30	98	4.5	9.9 × 100	2	200–500	10–200	3 h	[19]
Alginate beads				90 ± 2				2.5 mm	23.5 ± 2.78		[25]
Apricot stone		1.31 mg/kg		95	7–8	0.031 mg/kg	2 g	<63	200 mg/L	3–5 h	[29]
Ash, brick kiln			28	94 ± 0.8	7			Mesh 120	100 mg/L		[33]
Azolla filiculoides		93	25	95	3.5– 4.5		5		10–400		[37]
Bacteria, sulfate reducing	Batch	0.3						0.45		4 days	[40]
Bagasse fly ash (1998)	–	2.73 M/g	30	100	3.0	70.76 ± 1.0	10	150–200	0.000480 mol	6–8 h	[43]
Bagasse fly ash (2004)	Batch/column	3.8	30	95–96	6.0	11.44	10	200–250	5.0–70.0	60 min	[47]
Bed sediments				90	5		5	<75	2–25	30 min	[51]
Biomass of *Spirulina maxima*	Batch/column	Intact: 21, pretreated: 23	20	Intact: 84, pretreated: 92	5.5		2	150	50	60–180 min	[54]
Biomass, filamentous fungi	Batch	769			6						[61]
Biomass, *Mucor rouxil*, dead	Batch	53.75			6	0.27 L/mg	0.01–0.2	150	10	5 h	[59]
Biomass, *Mucor rouxil*, live	Batch	35.69			5	0.80 L/mg	0.01–0.2	150	10	7 h	[59]
Biomass, *Pinus sylvestris* cone		6.70	25	53.6	4		4	400 mesh copper sieve	50	1 h	[57]
Biosurfactant	Batch	30	Room	75	12	0.06	0.7	0.45	100		[65]
Bone powder	Synthetic and industrial wastewater	1.8×10^{-4} mol/g		100	6		0.1	0.2 mm	42	15 min	[68]
Carbon, activated	Synthetic and industrial wastewater	1.2×10^{-4} mol/g		90	6		0.1	0.2 mm	78	30 min	[72]
Carbon, commercial	Synthetic and industrial wastewater	8×10^{-5} mol/g		50	6		0.1	0.2 mm	90	120 min	
Carbonate hydroxyapatite		1.66	298 K	100	2–3	11.93	5		1000	30 min	[75]
Ceramics	Synthetic and industrial wastewater						0.1	0.2 mm			[71]
Cereal chaff	Batch	12.5	293 K		5.5	0.0920	0.1–0.6	104–102	8 g/L	30 min	[80]
Charcoal, natural	Batch	150			7			20 –100 mesh			[81]
Chitin, natural	Batch	264	308 K		4	2.13×10^{-2}	1	500	100–300	6 h	[83]
Chitin, phosphorylated	Batch	258	308 K		4	2.13×10^{-2}	1	500	100–300	6 h	[83]
Chitin, xanthated	Batch	316	308 K		4	2.13×10^{-2}	1	500	100–300	6 h	[83]
Chitins, surface modified											[83]
Chlorella vulgaris cells, dead				85 ± 1				2.5 mm	16.6 ± 0.57		[83]
Chlorella vulgaris cells, live				91.2 ± 2.25				2.5 mm	20.9 ± 1.86		[25]
Clinoptilolite, natural	Batch	166	20	50	2–4	0.0344	0.5	315–500	10	120 min	[99]
Cocoa shells	Shaken flasks	161 mmol/kg		95	2		15	>1 mm	3.66 mmol/L	24 h	[101]
Coconut		4.38	60		4	12.30	6	0.5–0.2 mm	100		[104]
Compost, leaf					6.5			<250	90 mg/kg		[107]

Duoite C-433 (synthetic resin)	Batch aqueous solution	0.07 mill mol/g	40		6.5 ± 0.1					90 min	[110]
Egg shells			28	90.8 ± 2.0	7			Mesh 120	100 mg/L		[105]
Ferrihydrite					5.5			<250	1000 mg/kg		[105]
Fish scale, Atlantic cod	Batch	80		100	4		4	35–40	2.5	72 h	[115]
Fly ash, bagasse	Column	2.50	30	95–96	6	0.021	10	200–250 μm	5.0 –70 mg/L	60 min	[117]
Fly ash, modified, activated	Batch	98 mmol/100 g solid	25	98	5	12.10 L/mmol	0.5–2		0.0027 mol/L	4 h	[120]
Green algae (*Spirogyra* species)	Batch aqueous solution	140	25	80	5.0		5–10	150–250	200	100 min	[124]
Iron material, recycled	Column	42.3			5.5		0.28	Mesh 60 × 80	10	1.26 min	[127]
Leaves, *Casurina glauca* tree	Batch			97.37	6.5		1/50 mL		25 mg/L	120 min	[131]
Maize cobs					2.5–4.5		2		25 mg/L	90–120 min	[133]
Okra waste	Batch	5	25	99	5			180–60	240	1.5 h	[136]
Palmyra palm fruit seed carbon	Batch	24.6	30	100	4		200 mg	120–140 ASTM mesh size	20	5 h	[139]
Peach stone		2.33 mg/kg		97.64	7–8	0.028 mg/kg	2 g	<63	200 mg/L	3–5 h	[29]
Pedogenic oxides SMS-1 SMS-2					6, 7			<250	500–800 mg/kg		[107]
Phaseolus vulgaris L.		100	25	72						5 days	[145]
Phosphate, activated	Batch	175.44	318 K		3–4	0.0476 L/mg	1	63	200	1–3 h	[148]
Phosphate, natural	Batch	131.75	318 K		2–3	1.0039 L/mg	1	63	200	1–3 h	[148]
Plant powder	Synthetic and industrial wastewater	9×10^{-5} mol/g		80	6		0.1	0.2 mm	85	45 min	[68]
Plantago major L.		100	25	77						5 days	[145]
Pseudomonas aeruginosa PU21 beads	Batch	0.735	332 K	70	5		10 g	3–3.5 mm	73.4	15 min	[154]
Red mud	Batch/column aqueous solution	Batch: 64.79. Column: 88.20	30	89	4	15.90×10^{-3} L/mol	10	150 –200 B.S.S mesh	4.83×10^{-3} M	24 h	[156]
Red soil		21.7			6						[157]
Rice husk				98.15	2.5–4.5		2		25 mg/L	90–120 min	[133]
Sago waste	Cooled orbital shaker	46.6	25 ± 5		4.5–5.5	0.246 L/mg	>3	<500	50–100	30–40 min	[158]
Sand, River Ravi			28	92.8 ± 2.3	7			Mesh 120	100 mg/L		[33]
Sawdust	Batch/column	13.9	23	98.8	2–5		40	30–60 mesh	5	3–24 h	[161]
Seaweed, brown	Batch and continuous	1.35 ± 0.07	30		4	20.2 ± 6.4 L/g mol	2.0			30 min	[163]
Seed hull		3.77	60		4	14.88	6	0.5–0.2 mm	100		[104]
Sepiolite, natural	Batch	185.2	50		4–6	0.2090	0.25 g	300–500	50	60 min	[130]
Silicate MCM-41, mesoporous				99	6.8		0.1 g	3.12 nm		24 h	[167]
Slag, granular	Batch with Columns	8.05		51	4		2.15	500–1600	20		[169]
Soil, fine loamy			298– 318		4– 7					24	[170]
Staphylococcus saprophyticus		100 mg/L	27	100	4.5				100	4 h	[173]
Sugar beet pectin gels	Batch	0.5 mmol/g			5		1		100	2 h	[174]
Tea waste			28	92.8 ± 1.3	7			Mesh 120	100 mg/L		[33]
Vegetable biomass		7380 μg/g	25							36 h	[177]
Zeolite tuff		1.158 meq/g	20		4–4.5		2 g/L	90–180 ASTM sieve	2.413 meq/L		[178]
Zeolites, Amasya		34.48		>98							[179]

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