**Supplementary data**

**Occurrence of Contaminants in Drinking Water Sources and the Potential of Biochar for Water Quality Improvement: A Review**

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Table S1. Adsorption capacity of different biochar for microbial, inorganic, and organic contaminants in aqueous solutions.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Order** | **BC feed stock**  **Pyro.temp. (oC)/ duration** | **BC treatment** | **Used BC quantity** | **Used method (technique)** | **Contaminant** | **Initial conc. of adsorbate** | **Adsorption capacity** | **References** |
|  |  |  |  |  | **Inorganic** |  |  |  |
| 01 | Spent mushroom compost  500/2h | Aluminum hydroxide-coated BC | 0.4–8.0 g/L | Batch adsorption experiments | Fluoride | 5–100 mg/L  (pH 6.0–8.0) | 36.5 mg/g | (Chen et al., 2016) |
| 02 | Woody yard wastes  500/15h | Original BC | 25g/L | Batch adsorption experiments with permeable reactive barriers | Copper | 2 - 500 mg/L | 7.51 mg/g | (Beiyuan et al., 2017) |
| Zinc | 2.44 mg/g |
| Lead | 10.2 mg/g |
| 03 | Bagasse  300/2h | BC+polysulfone mixed matrix hollow fiber membrane | 0.5g/L | Batch adsorption experiment with mixed matrix membrane technique | Copper | 12.8 mg/L  (pH 5) | 24.47 mg/g | (He et al., 2017) |
| Lead | 0.21 mg/L  (pH 5) | 79.76 mg/g |
| 04 | Sewage sludge 400/2h | Magnetic BC, Fe2+/Fe3+ plus SO42-solution without ZnCl2 | 2 g/L | Batch adsorption experiments | Lead | 20-1000 mg/L | 99.85 mg/g | (Ifthikar et al., 2017) |
| Magnetic BC, Fe2+/Fe3+ plus SO42-solution with ZnCl2 | 249 mg/g |
| 05 | Douglas fir  900-1000/1-10 s | Original BC | 2 g/L | Batch adsorption experiments | Lead | 10 – 250 mg/L (pH 5) | 37.7 mg/g (25oC) | (Karunanayake et al., 2018) |
| 38.2 mg/g (35oC) |
| 39.8 mg/g (45oC) |
| Cadmium | 14.6 mg/g (25oC) |
| 15.7 mg/g (35oC) |
| 16.0 mg/g (45oC) |
| Fe3O4-magnetized BC | Lead | 26.0 mg/ (25oC) |
| 26.0 mg/g (35oC) |
| 26.8 mg/g (45oC) |
| Cadmium | 11.0 mg/g (25oC) |
| 11.1 mg/g (35oC) |
| 11.3 mg/g (45oC) |
| 06 | Water hyacinth 250/1h | Fe2/Fe3 Co-precipitated magnetic BC | 1:200 (solid: solution v/v) | Batch adsorption experiments | As(V) | 2 -105 mg/L  (pH 5.3) | 7.41 mg/g | (Zhang et al., 2016) |
|
| 07 | Hickory chips 600/2h | Fe-impregnated BC | 2g/L | Batch adsorption experiments | As(V) | 0.1- 55 mg/L  (pH ~5.8) | 2.16 mg/g | (Hu et al., 2015) |
| 08 | Chestnut shell  450/2h | Magnetic gelatin-modified BC | 0.4g/L | Batch adsorption experiments | As(V) | 0.2–50 mg/L  (pH 4) | 43.15 mg/g (25oC) | (Zhou et al., 2017) |
| 46.89 mg/g (35oC) |
| 49.15 mg/g (45oC) |
| 09 | Oak wood ~500/NA | Original BC | 1 g/L | Batch adsorption experiments | As (III) | 0.05-7.0 mg/L  (pH 7.0) | ~3.16 mg/g | (Niazi et al., 2017b) |
| As(V) | 0.05-7.0 mg/L  (pH 6.0) | ~3.89 mg/g |
| 10 | Perilla leaves 300/NA | Original BC | 1 g/L | Batch adsorption experiments | As (III) | 0.05-7.0 mg/L  (pH ~7.0) | ~ 4.71 mg/g | (Niazi et al., 2017a) |
| Perilla leaves 700/NA | As (III) | ~11.01 mg/g |
| Perilla leaves 300/NA | As (V) | ~3.85 mg/g |
| Perilla leaves 700/NA | As(V) | ~7.21 mg/g |
| 11 | NA | Fe2O3 supported CNT | 0.5 g/L | Batch adsorption experiments | Sb (III) | 1.5 mg/L (pH 7) | 6.23 mg/g | (Yu et al., 2013) |
| 12 | Pine sawdust 300/2h | Original BC | 3 g/L | Batch adsorption experiments | Ammonium | 10 - 100 mg/L (pH 7) | 5.38 mg/g | (Yang et al., 2017) |
|  | Pine sawdust 550/2h | 3.37 mg/g |
|  | Wheat straw 550/2h | 2.08 mg/g |
| 13 | Hickory chips 600/1h | Sodium dodecyl benzene sulfonate modified CNT-BC nanocomposites | 2mg/L | Batch adsorption experiments | Lead | 40 mg/L | 15.2 mg/g | (Inyang et al., 2015) |
|  | Sugarcane bagasse  600/1h | 13.7 mg/g |
| 14 | Orange peel 250/6h | Magnetic BC | NA | Batch adsorption experiments | Phosphate | 0-12 mg/L | 0.512 mg/g | (Chen et al., 2011) |
|  | Orange peel 400/6h | 0.219 mg/g |
|  | Orange peel 700/6h | 1.24 mg/g |
| 15 | Corn straw 400/2h | Iron modified BC | 1g/L | Batch adsorption experiments | Phosphate | 2.2- 12 mg/L | 0.56 mg/g | (Liu et al., 2015) |
| 16 | Pine sawdust  300-500/2h | Steam activated BC | 2 g/L | Batch adsorption experiments | Phosphate | 0-40 mg/L  (pH 7) | 1.0 -1.4 mg/g | (Lou et al., 2016) |
| 17 | Conocarpus green waste  600/4h | Original BC | 10 g/L | Batch adsorption experiments | Nitrate | 1–200 mg/ L  (pH 6) | 16.47 mmol/kg | (Usman et al., 2016) |
| MgO-BC | 45.36 mmol/kg |
| FeO-BC | 20.27 mmol/kg |
|  |  |  |  |  | **Organic** |  |  |  |
| 18 | Water hyacinth/350 | Original BC | 2-10 mg/L | Batch adsorption experiments | Caffeine | 5 mg/L | 2.488 mg/g | (Ngeno et al., 2016) |
| 19 | Douglas fir/ 900–1000 | Magnetic  BC | 2 g/L | Batch adsorption experiments | Salicylic acid | 25-500 mg/L | 89.91 mg/g (15oC)  92.42 mg/g (25oC)  96.17 mg/g (35oC)  108.78 mg/g (45oC) | (Karunanayake et al., 2017) |
| 20 | Pine wood/425 | Original BC | 4 g/L | Batch adsorption experiments | Salicylic acid | 25 - 100 mg/L | 7.56 mg/g (25oC)  16.84 mg/g (35oC)  22.70 mg/g (45oC) | (Essandoh et al., 2015) |
| 21 | Switchgrass  425/1h | Original BC | 2 g/L | Batch adsorption experiments | Metribuzin | 40–400 mg/L | 151 mg/g (25oC) | (Essandoh et al., 2017a) |
| 223 mg/g (35oC) |
| 206 mg/g (45oC) |
| Magnetic switchgrass BC | 155 mg/g (25oC) |
| 205 mg/g (35oC) |
| 155 mg/g (45oC) |
| 22 | Tea waste/700  Tea waste/700  Burcucumber/700  Oak wood/400  Bamboo/400 | Original BC  Steam activation  Original BC  Original BC  Original BC | 2.5g/L | Batch adsorption experiments | 2,4-Dichlorophynoxy acetic acid | 10-500 mg/L  (pH 7) | 10.05 mg/g  58.85 mg/g  42.67 mg/g  26.66 mg/g  28.92 mg/g | (Mandal et al., 2017) |
| 23 | Switchgrass  425/60s | Original BC | 1 g/L | Batch adsorption experiments | 2,4-Dichlorophenoxy acetic acid | 25-400 mg/L | 133 mg/g (25oC) | (Essandoh et al., 2017b) |
| 134 mg/g (35oC) |
| 129 mg/g (45oC) |
| 2-methyl-4- chlorophenoxyacetic acid | 50-150 mg/L | 38.31 mg/g (25oC) |
| 50.01 mg/g (35oC) |
| 50.01 mg/g (45oC) |
| 24 | Bamboo  380/2h | H3PO4-modified BC | 0.1g/L | Batch adsorption experiments | Sulfathiazole | 0.5–50 mg/L | 237.71 mg/g | (Ahmed et al., 2017) |
| Sulfamethazine | 65.74 mg/g |
| Sulfamethoxazole | 88.1 mg/g |
| 25 | Orange peel 250/6h | Original BC | NA | Batch adsorption experiments | Naphthalene | 0.02-0.95$ | 2.99 mg/g | (Chen et al., 2011) |
|  | Orange peel  400/6 h | Original BC | 9.39 mg/g |
|  | Orange peel  250/6 h | Magnetic BC | 0.835 mg/g |
|  | Orange peel  400/6 h | Magnetic BC | 23 mg/g |
|  | Orange peel  250/6 h | Original BC | p-nitrotoluene | 0.01 to 0.91$ | 7.44 mg/g |
|  | Orange peel  400/6 h | Original BC | 29.7 mg/g |
|  | Orange peel  250/6 h | Magnetic BC | 2.22 mg/g |
|  | Orange peel  400/6 h | Magnetic BC | 43.4 mg/g |
| 26 | Bamboo  550/NA | Original BC | 75 g/L | Batch adsorption experiments | Furfural | 5000 mg/L -20000 mg/L | 109.17 mg/g | (Li et al., 2014) |
| Oxidation by KMnO4 | 93.55 mg/g |
| Oxidation by HNO3 | 96.34 mg/g |
| Treated with NaOH | 102.04 mg/g |
| Heat treatment | 253.16 mg/g |
| 27 | Rice husk  300/3h | Original BC | 1 g/L | Batch adsorption experiments | Carbofuran | 5-100 mg/L  (pH 5) | 30.73 mg/g | (Mayakaduwa et al., 2016) |
|  | Rice husk 500/3h |  | 48.75 mg/g |
|  | Rice husk 700/3h |  | 132.87 mg/g |
|  | Rice husk 700/3h | Steam activated BC |  | 160.77 mg/g |
| 28 | Hickory chips 600/1h | Sodium dodecyl benzene sulfonate modified CNT-BC nanocomposites | 2g/L | Batch adsorption experiments | Sulfapyridine | 20 mg/L | 27.9 mg/g | (Inyang et al., 2015) |
|  | Sugarcane bagasse  600/1h | 19.36 mg/g |
| 29 | Castor oil cake  400/1h | HNO3 activated BC | 10% BC (w/w) | Carbon paste modified electrode with BC activated by HNO3  (drinking water) | Methyl parathion | 1.0 × 10−4 mol/L (pH 5) | 0.76 μA L/μmol# | (de Oliveira et al., 2017) |
| Original BC | 0.46 μA L/μmol# |
| 30 | Grass straw 400/1h | Original BC | 0.005-0.2g/L | Batch adsorption experiments | Phenanthrene | 0.002–1.10 mg/L | 3.89 - 5.33 mL/g Ɨ | (Jin et al., 2017) |
| Oxidizion by HNO3 | 4.25 - 5.67 mL/g Ɨ |
| Animal waste 400/1h | Original BC | 3.51 - 5.56 mL/g Ɨ |
|  | Oxidizion by HNO3 | 2.70 - 5.39 mL/g Ɨ |
| 31 | loblolly pine chips with bark  300/15min | NaOH activated oxygen-based BC | 0.005-0.05g/L | Activated BC-ultrafiltration hybrid system | Humic acid | 5 mg/L | 1.230 mg/g | (Chu et al., 2017) |
| NaOH activated nitrogen-based BC | 1.306 mg/g |
|  |  |  |  |  | **Microbial** |  |  |  |
| 32 | Willow wood  300/NA | HCl treated BC | 25g/L | Batch adsorption experiments | Deoxyribonucleic acid (DNA) | 20 - 40 mg/L | 1.89 mg/g | (Wang et al., 2014) |
|  | Willow wood  400/NA | 2.52 mg/g |
|  | Willow wood  500/NA | 5.73 mg/g |
|  | Willow wood  600/NA | 5.15 mg/g |

BC: Biochar

NA: Not Available

# Electrode sensitivity

ƗlogKd (Kd = solid phase concentrations of sorbate/ solution phase concentrations of sorbate)

$Relative initial concentrations = initial concentration/aqueous solubility

**References**

Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W., Johir, M.A.H., Sornalingam, K. 2017. Single and competitive sorption properties and mechanism of functionalized biochar for removing sulfonamide antibiotics from water. *Chemical Engineering Journal*, **311**, 348-358.

Beiyuan, J., Tsang, D.C., Yip, A.C., Zhang, W., Ok, Y.S., Li, X.-D. 2017. Risk mitigation by waste-based permeable reactive barriers for groundwater pollution control at e-waste recycling sites. *Environmental geochemistry and health*, **39**(1), 75-88.

Chen, B., Chen, Z., Lv, S. 2011. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. *Bioresource technology*, **102**(2), 716-723.

Chen, G.-j., Peng, C.-y., Fang, J.-y., Dong, Y.-y., Zhu, X.-h., Cai, H.-m. 2016. Biosorption of fluoride from drinking water using spent mushroom compost biochar coated with aluminum hydroxide. *Desalination and Water Treatment*, **57**(26), 12385-12395.

Chu, K.H., Shankar, V., Park, C.M., Sohn, J., Jang, A., Yoon, Y. 2017. Evaluation of fouling mechanisms for humic acid molecules in an activated biochar-ultrafiltration hybrid system. *Chemical Engineering Journal*.

de Oliveira, P.R., Kalinke, C., Gogola, J.L., Mangrich, A.S., Junior, L.H.M., Bergamini, M.F. 2017. The use of activated biochar for development of a sensitive electrochemical sensor for determination of methyl parathion. *Journal of Electroanalytical Chemistry*.

Essandoh, M., Kunwar, B., Pittman, C.U., Mohan, D., Mlsna, T. 2015. Sorptive removal of salicylic acid and ibuprofen from aqueous solutions using pine wood fast pyrolysis biochar. *Chemical Engineering Journal*, **265**, 219-227.

Essandoh, M., Wolgemuth, D., Pittman, C.U., Mohan, D., Mlsna, T. 2017a. Adsorption of metribuzin from aqueous solution using magnetic and nonmagnetic sustainable low-cost biochar adsorbents. *Environmental Science and Pollution Research*, **24**(5), 4577-4590.

Essandoh, M., Wolgemuth, D., Pittman, C.U., Mohan, D., Mlsna, T. 2017b. Phenoxy herbicide removal from aqueous solutions using fast pyrolysis switchgrass biochar. *Chemosphere*, **174**, 49-57.

He, J., Song, Y., Chen, J.P. 2017. Development of a novel biochar/PSF mixed matrix membrane and study of key parameters in treatment of copper and lead contaminated water. *Chemosphere*, **186**, 1033-1045.

Hu, X., Ding, Z., Zimmerman, A.R., Wang, S., Gao, B. 2015. Batch and column sorption of arsenic onto iron-impregnated biochar synthesized through hydrolysis. *water research*, **68**, 206-216.

Ifthikar, J., Wang, J., Wang, Q., Wang, T., Wang, H., Khan, A., Jawad, A., Sun, T., Jiao, X., Chen, Z. 2017. Highly Efficient Lead Distribution by Magnetic Sewage Sludge Biochar: Sorption Mechanisms and Bench Applications. *Bioresource technology*, **238**, 399-406.

Inyang, M., Gao, B., Zimmerman, A., Zhou, Y., Cao, X. 2015. Sorption and cosorption of lead and sulfapyridine on carbon nanotube-modified biochars. *Environmental Science and Pollution Research*, **22**(3), 1868-1876.

Jin, J., Sun, K., Wang, Z., Han, L., Du, P., Wang, X., Xing, B. 2017. Effects of chemical oxidation on phenanthrene sorption by grass-and manure-derived biochars. *Science of The Total Environment*, **598**, 789-796.

Karunanayake, A.G., Todd, O.A., Crowley, M., Ricchetti, L., Pittman Jr, C.U., Anderson, R., Mohan, D., Mlsna, T. 2018. Lead and cadmium remediation using magnetized and nonmagnetized biochar from Douglas fir. *Chemical Engineering Journal*, **331**, 480-491.

Karunanayake, A.G., Todd, O.A., Crowley, M.L., Ricchetti, L.B., Pittman, C.U., Anderson, R., Mlsna, T.E. 2017. Rapid removal of salicylic acid, 4-nitroaniline, benzoic acid and phthalic acid from wastewater using magnetized fast pyrolysis biochar from waste Douglas fir. *Chemical Engineering Journal*, **319**, 75-88.

Li, Y., Shao, J., Wang, X., Deng, Y., Yang, H., Chen, H. 2014. Characterization of modified biochars derived from bamboo pyrolysis and their utilization for target component (furfural) adsorption. *Energy & Fuels*, **28**(8), 5119-5127.

Liu, F., Zuo, J., Chi, T., Wang, P., Yang, B. 2015. Removing phosphorus from aqueous solutions by using iron-modified corn straw biochar. *Frontiers of Environmental Science & Engineering*, **9**(6), 1066-1075.

Lou, K., Rajapaksha, A.U., Ok, Y.S., Chang, S.X. 2016. Pyrolysis temperature and steam activation effects on sorption of phosphate on pine sawdust biochars in aqueous solutions. *Chemical Speciation & Bioavailability*, **28**(1-4), 42-50.

Mandal, S., Sarkar, B., Igalavithana, A.D., Ok, Y.S., Yang, X., Lombi, E., Bolan, N. 2017. Mechanistic insights of 2, 4-D sorption onto biochar: Influence of feedstock materials and biochar properties. *Bioresource technology*, **246**, 160-167.

Mayakaduwa, S., Herath, I., Ok, Y.S., Mohan, D., Vithanage, M. 2016. Insights into aqueous carbofuran removal by modified and non-modified rice husk biochars. *Environmental Science and Pollution Research*, 1-9.

Ngeno, E., Orata, F., Lilechi, D., Shikuku, V.O., Kimosop, S. 2016. Adsorption of caffeine and ciprofloxacin onto pyrolytically derived water hyacinth biochar: Isothermal, kinetics and thermodynamics. *Journal of Chemistry and Chemical Engineering*, **10**, 185-194.

Niazi, N.K., Bibi, I., Shahid, M., Ok, Y.S., Burton, E.D., Wang, H., Shaheen, S.M., Rinklebe, J., Lüttge, A. 2017a. Arsenic removal by perilla leaf biochar in aqueous solutions and groundwater: An integrated spectroscopic and microscopic examination. *Environmental Pollution*.

Niazi, N.K., Bibi, I., Shahid, M., Ok, Y.S., Shaheen, S.M., Rinklebe, J., Wang, H., Murtaza, B., Islam, E., Nawaz, M.F. 2017b. Arsenic removal by Japanese oak wood biochar in aqueous solutions and well water: Investigating arsenic fate using integrated spectroscopic and microscopic techniques. *Science of The Total Environment*.

Usman, A.R., Ahmad, M., El-Mahrouky, M., Al-Omran, A., Ok, Y.S., Sallam, A.S., El-Naggar, A.H., Al-Wabel, M.I. 2016. Chemically modified biochar produced from conocarpus waste increases NO3 removal from aqueous solutions. *Environmental geochemistry and health*, **38**(2), 511-521.

Wang, C., Wang, T., Li, W., Yan, J., Li, Z., Ahmad, R., Herath, S.K., Zhu, N. 2014. Adsorption of deoxyribonucleic acid (DNA) by willow wood biochars produced at different pyrolysis temperatures. *Biology and fertility of soils*, **50**(1), 87-94.

Yang, H.I., Lou, K., Rajapaksha, A.U., Ok, Y.S., Anyia, A.O., Chang, S.X. 2017. Adsorption of ammonium in aqueous solutions by pine sawdust and wheat straw biochars. *Environmental Science and Pollution Research*, 1-10.

Yu, T., Zeng, C., Ye, M., Shao, Y. 2013. The adsorption of Sb (III) in aqueous solution by Fe2O3-modified carbon nanotubes. *Water Science and Technology*, **68**(3), 658-664.

Zhang, F., Wang, X., Xionghui, J., Ma, L. 2016. Efficient arsenate removal by magnetite-modified water hyacinth biochar. *Environmental Pollution*, **216**, 575-583.

Zhou, Z., Liu, Y.-g., Liu, S.-b., Liu, H.-y., Zeng, G.-m., Tan, X.-f., Yang, C.-p., Ding, Y., Yan, Z.-l., Cai, X.-x. 2017. Sorption performance and mechanisms of arsenic (V) removal by magnetic gelatin-modified biochar. *Chemical Engineering Journal*, **314**, 223-231.