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Life Cycle Environmental and Economic Performance of Biochar Compared with Activated Carbon: A Meta-Analysis

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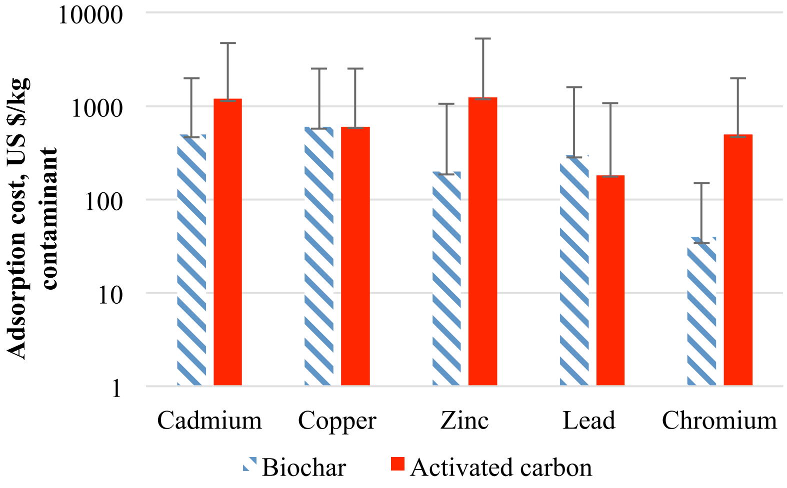
Highlights

- Average energy demands were 6.1 MJ/kg biochar and 97 MJ/kg activated carbon
- Cost of biochar lower than activated carbon to adsorb chromium and zinc
- Cost of biochar comparable to activated carbon to adsorb lead and copper
- Biochar has lower impacts than activated carbon even after transportation phase



Abstract:

As the commercial production and distribution of biochar continues to grow internationally, and its applications diversifying from its early uses as soil amendment, it is important to study the environmental impacts and economic performance of biochar in comparison to activated carbon in order to assess its value. The goal of the study was to assess, through a meta-analysis, the environmental and economic performance of biochar in comparison to activated carbon under an equivalent functional unit to adsorb heavy metals. More than 80 data points on adsorption capacity of biochar and activated carbon were identified through literature, which were statistically analyzed as part of the study. Biochar was found to have lower energy demand and global warming potential impact than activated carbon, where average energy demands were calculated as 6.1 MJ/kg and 97 MJ/kg and average greenhouse gas emissions calculated as -0.9 kg CO_2eq/kg and 6.6 kg CO_2eq/kg for biochar and activated carbon, respectively. When adsorption of heavy metals were used as the functional unit during analysis, results indicate that there is typically an order of magnitude difference between the two materials, where biochar was found to have lower environmental impacts. The environmental impact resulting from long distance transportation of biochar would not overturn this conclusion. The adsorption cost of biochar was lower than activated carbon to remove chromium and zinc with a 95% confidence. Adsorption cost for lead and copper were found to be comparable, and therefore the specific type of biochar and its price could shift results both ways. There is evidence that biochar, if engineered correctly for the task, could be at least as effective as activated carbon and at a lower cost.

Keywords

Biochar; Activated carbon; Heavy metal adsorption; Environmental impact; Economic analysis; Transportation impact.

1. Introduction

Biochar is an effective bio-sorbent with a high carbon content varying from 50% to 93%, produced by pyrolysis of biomass within a closed system with oxygen levels below 0.5% (Ahmad et al., 2013; Anderson et al., 2013; Antal M.J., Mochidzuki and Paredes, 2003; Clough and Condron, 2010; Inyang et al., 2012; Libra et al., 2011; Liu et al., 2012; Meyer et al., 2012, 2011; Nhuchhen et al., 2014; Roberts et al., 2010; Sohi et al., 2010; Yan et al., 2009). Biochar is typically produced from materials that are naturally abundant such as agricultural residue, animal waste, or refuse of woody plants, that have high carbon content. The raw material together with the production technique and temperature has an important effect on product yield and composition (Ahmad et al., 2013; Amutio et al., 2012; Boateng et al., 2010; B. Chen et al., 2011; Chen et al., 2008; X. Chen et al., 2011; Garcia-Nunez et al., 2016; Hammond et al., 2011; Harsono et al., 2013; Helleur et al., 2001; Inyang et al., 2012; Kołodyńska et al., 2012; Libra et al., 2011; Liu and Zhang, 2009; Medic, 2012; Mohan et al., 2011; Oleszczuk et al., 2012; Park et al., 2011; Pellera et al., 2012; Regmi et al., 2012; Ro et al., 2010; Roberts et al., 2010; Sohi et al., 2009; Woolf et al., 2010a; Yao et al., 2012, 2011a; P. Zhang et al., 2013).

Traditional processes and technologies that have been utilized for the removal of heavy metals from water and wastewater include chemical precipitation, ion exchange, chemical oxidation and reduction, filtration, membrane technology (separation), reverse osmosis, electrochemical treatment, electrodialysis, electroflotation, electrolytic recovery, and adsorption by activated carbon (El-Ashtoukhy et al. 2008; Inyang et al. 2012; Pellera et al. 2012; Zheng et al. 2008). Most of these technologies require high operating energy and thereby cost, and also bring together environmental impacts associated with operating energy consumption.

While biochar has been used by humans for centuries as a soil supplement, the material has received recognition in recent years in part due to its adsorption properties, which are claimed to be comparable to activated carbon. Studies suggest that biochar is effective for the removal of heavy metals and other contaminants from municipal wastewater as well as from industrial wastewater (X. Chen et al., 2011; Han et al., 2013; Inyang et al., 2012, 2011; Jiang et al., 2012; Karim et al., 2015; Kılıç et al., 2013; Li et al., 2013; Liu and Zhang, 2009; Park et al., 2011; Pellera et al., 2012; Pérez-Marín et al., 2007; Regmi et al., 2012; Sun et al., 2011; Tong et al., 2011; Xu et al., 2011, 2013; Yao et al., 2011b; P. Zhang et al., 2013; X. Zhang et al., 2013; Zheng et al., 2008). As a result, the commercial production and distribution of biochar continues to grow internationally, and its applications diversifying and moving up from its early uses as a soil amendment. To that end, it is important to study the environmental impacts of biochar in comparison to alternative materials such as activated carbon in order to assess its impacts or potential advantages, both from an environmental impact perspective as well as economically.

The goal of the study was to assess, through a meta-analysis, the environmental and economic performance of biochar when used as an adsorbent for heavy metals in comparison to activated carbon. The study enables a comparison between the two materials by using a realistic functional unit for adsorption rather than using mass or volume for comparison. The results of the meta-analysis are statistically stronger than the results of a single study due to increased sample size and data analysis, and as less emphasis is being placed on inherently localized boundaries, materials, and assumptions made in studies. The impact of long distance or international trade on environmental impacts of biochar were also investigated as part of the study.

2. Methods

2.1 Evaluating the environmental impact of biochar and activated carbon

Data on the environmental impact of biochar and activated carbon were collected mainly through peer-reviewed journal articles on life cycle assessment (LCA) of biochar and activated carbon. A total of 84 different types of biochar and activated carbon were identified from literature, and corresponding data recorded. However, as is typical with most LCA studies, the results were based on a particular product, for a specific case. Furthermore, the majority of LCA studies did not report results other than for energy demand and global warming potential (GWP). While there were several data points for photochemical oxidation, acidification, and eutrophication impact categories, they were not sufficient for a statistical analysis and therefore were not included in the scope of the study. A lack of environmental impact data was a big impediment to study other impact categories such as human toxicity; abiotic depletion; ozone layer depletion; and aquatic ecotoxicity.

Conversion factors were necessary to convert units of certain environmental impact categories to known equivalents. GWP of CH_4 and N_2O were calculated by converting their emissions to CO_2 equivalent units. The unit conversion factors were taken from the Environment Protection Agency (EPA) report on greenhouse gas (GHG) inventories (EPA 2014). Energy consumption was also converted to MJ/kg when reported in other units.

Data points for biochar and activated carbon made from similar materials obtained from different sources were condensed to bring down the number of different products to manageable levels. For example, the differences in environmental impacts of early and late corn stover, the main difference being moisture content, were neglected and the two were integrated into one product category as corn stover, as the differences between the two were expected to be negligible when compared to differences among other products, or when compared to activated carbon, the main intent of the study. Similarly, some other studies had analyzed multiple scenarios for the same product based on different intended use, production quantity, or production method, thus presenting multiple data points in each case. In those cases, the range of results was used in the study.

The statistical analysis tool @Risk version 7 was used to analyze environmental impacts of biochar and activated carbon resulting from adsorption of heavy metals. The chi-squared test was used to fit distributions for each set of adsorption capacity and environmental impact. Monte Carlo analysis was conducted to analyze environmental impacts of biochar and activated carbon resulting from adsorption of heavy metals. Monte Carlo analysis uses random inputs from a given dataset and outputs possible results in the form of probability distribution (Palisade, 2013). This analysis was performed using 10,000 iterations. The results of the simulation for each contaminant were fitted with a distribution to evaluate the environmental impact of biochar and activated carbon per adsorption capacity. The mean for the distributions and a 95% confidence interval for each heavy metal were also calculated and reported in the study.

2.2 The adsorption capacities of biochar and activated carbon

Some adsorption capacity data were reported in millimoles per kilogram or gram, and these values were converted to milligram per gram (mg/g). Other physical property or test conditions such as particle size, surface area, concentration of contaminants, pH, and adsorbent dose were also reported in this study.

A large number of different raw materials that may be used for biochar production were surveyed from literature rather than limit the study on experimental environmental conditions such as temperature and relative humidity for a specific raw material. There were two reasons behind this decision. The goal of this study was to identify overall trends in data through a meta-analysis for biochar and activated carbon rather than to conduct a LCA for a particular product as a case study. Secondly, there is significant lack of reported data on the effects of these variables on adsorption, especially for biochar. The goal was not to test adsorption for its own sake, but rather to tie performance to environmental and economic value in general terms.

2.3 Evaluating the economic performance of biochar compared to activated carbon

To assess the economic performance of biochar in comparison to activated carbon when used for adsorption purposes, the adsorption capacity of each material together with their market prices were used. The metric used for comparison was therefore US$(2015)/kg adsorbed material.

Current market value prices for different types of biochar and activated carbon were sought during the study. Values reported in scholarly publications and online listing of companies from around the world commercially trading biochar was used to gather market price data (Rasmussen 2014). Most of the companies that were located on the directory were from developed countries; namely the U.S., Canada, Australia, and several Western European countries, and a few were from developing countries such as India and Turkey. All companies listed on the directory were contacted by email to inquire regarding price and raw material used to produce biochar.

Most companies sold biochar by volume rather than mass or weight, which was the preferred unit used in this study for adsorption calculations. It was found out that the practical reason for this was to enable biochar to be shipped wet to avoid dust problems that may arise when shipped dry, while the removal of volatile carbon during shipping could also lead to problems in a business transaction if the material were sold by mass. Biochar density data were analyzed statistically to convert volume to mass. Data were analyzed statistically and the mean of the biochar density data was used in this study, thus enabling the conversion of price into US$(2015)/kg biochar.

Similar to adsorption calculations, the statistical analysis tool @Risk version7 was used to compare adsorption cost for heavy metals. The chi-squared test was used to fit distributions for each set of adsorption capacity and price. After the data sets were converted to distributions, Monte Carlo simulation with 10,000 iterations was used to setup distributions for adsorption cost of biochar and activated carbon for each heavy metal analyzed. The mean for the distributions of adsorption costs and a 95% confidence interval for each heavy metal were also reported.

2.4 Assessing the impact of long distance trade on environmental performance of biochar

2.4.1 Selecting locations for analysis

Different locations from different continents and regions were used as scenario variables in order to estimate the impact of long distance trade on the environmental performance of biochar. The analysis included fifteen locations, where the majority of locations were chosen based on the directory of companies commercially selling biochar. Three countries which were not in the directory were added to capture remaining regions and continents. While selecting locations for the analysis were intended to cover the majority of potential trade routes, what is important to assess impacts of long distance trade is not the location or the country itself, but the distance between the two locations where transportation occurs.

2.4.2 Estimating the distance between selected locations

To calculate the added energy consumption and GHG emissions as a result of long distance trade of one metric ton of biochar, land and sea distances between selected locations had to be estimated. For distances that could be traversed by land routes, the publicly available online Google Maps tool was used to estimate distance (Google Maps 2015). For routes that required sea transport, an online resource was used to estimate distances from port to port (Searates 2015). In such cases, the land routes required to transport goods to and from respective ports were also included in the analysis.

As the goal of this step of the analysis was to gain insights into the overall impacts of long distance trade on environmental performance, rather than specifically determine impacts for an individual transaction, the center of each state was used to estimate impacts when the locations were inside the U.S. When countries were used, their capital cities were chosen to represent the point of destination and departure for biochar. The distances and impacts reported in this study could be used as a guide to estimate impacts of long distance or international trade that might occur between two other locations not captured by the selected 15 sites in the analysis, but with comparable distances between them, as impacts calculated here were dependent on distance and mode of travel rather than country or continent. The wide array of locations from across the globe was chosen with that additional intent.

2.4.3 Calculating energy demand

Calculating energy required to transport biochar required information on energy intensity of land and sea transportation. Energy intensity of sea transportation was taken as 0.14 MJ/ton-km based on literature (Davis et al., 2014). Trucks rather than rail were assumed for land transportation initially. A fuel consumption factor of 15.3 liter per thousand ton-km was used for class 8 truck transport, which uses diesel fuel, and includes combination trucks and tractor-trailers among other more specific uses (Davis et al., 2014). The fuel consumption factor was converted to truck transportation energy intensity by multiplying by the low heat value for diesel, which was found to be 128,450 Btu/gallon diesel (Boundy et al. 2011; DOE 2014). The resulting energy intensity of 0.55 MJ/ton-km was used in the calculations thereafter. Multiplying the land distance by the energy intensity provided the energy required to transport biochar by trucks. Total transportation energy consumption was found by adding together the energy consumptions of sea and land transportation.

A further analysis was conducted to test the effect of using the center of states in the U.S. on the impact resulting from transportation. Farther and nearer points on the border of the states, rather than the center point of the state, were selected to check their effect on the values of energy demand and GHG emissions. The effect of using truck rather than rail for transportation over land was also investigated through a sensitivity analysis.

2.4.4 Calculating greenhouse gas emissions

GHG emissions of transportation were calculated by using emission factors for GHG inventories used by the EPA (EPA 2014). The cumulative GHG emitted from waterborne craft were estimated by multiplying the nautical distance between ports with the transportation emission factor, which was 0.026 kg CO_2 eq. per ton-km (EPA 2014). GHG emissions of truck transportation were calculated by multiplying the land distance by 0.185 kg CO_2 eq. per ton-km (EPA 2014). The two values for the two respective modes of transport were added together to estimate GHG emissions resulting from long distance or international trade of biochar among selected locations.

3. Results and discussion

3.1 Environmental impact of biochar compared with activated carbon

Environmental impact data related to the production of biochar and activated carbon reviewed from literature were used for comparison. Energy demand and GWP were two categories considered in this study, and results were summarized in Table 1. Although environmental impact data based on different raw materials used for production of activated carbon were limited, a diverse list was found for raw materials that can be used for biochar production including many types of organic wastes, woods and residual plants that indicate increased adaptability of biochar production to local conditions.

Table 1. Energy demand and global warming potential of biochar and activated carbon. Values for energy demand indicate production energy unless noted otherwise. (Bartocci et al., 2016; Bayer et al., 2005; Dang et al., 2015; Gabarrell et al., 2012; Gaunt and Lehmann, 2008; Hammond et al., 2011; Hjaila et al., 2013; Ibarrola et al., 2011; Johnsen et al., 2016; Meyer et al., 2012; Muñoz et al., 2007; Peters et al., 2015; Roberts et al., 2010; Sparrevik et al., 2013; Woolf et al., 2010b)**.**

Material Type	Energy demand, MJ/kg	Global Warming Potential, kg CO_2eq/kg
Activated carbon (Virgin), hard coal	44 [a]	3, 3 [a], 8, 11
Activated carbon, olive-waste	170	11
Activated carbon, Recycled		1.2
Activated carbon, Granular	79.8	9.3
Agroforestry biochar		-0.2
Anaerobic digestion biochar	1.1 [a, b]	-0.7
Barley straw biochar	1.1 – 2.2 [b]	-0.7 – -0.9

Biomass crops biochar (herbaceous)		-0.2
Biomass crops biochar (woody)		-0.2
Canadian forestry residue chips biochar	1.4 – 2.9 [b]	-0.9 – 1.1
Cardboard biochar	1.8 [a, b]	-0.1
Cattle manure biochar		-0.2
Cereals excluding rice biochar		-0.2 – -0.1
Corn Stover biochar	0.84, 1.5-3 [a], 8	-0.7 – -0.8, -4 – -2
Dense refuse derived fuel	1.8 [a, b]	-0.3
Food waste biochar	1.3 [a, b]	-1.1
Forestry residue chips biochar	1.4 – 2.9 [b]	-1.3 – -1.1, -0.2 – -0.1
Green waste biochar	1.8 [a, b]	-1.1, -0.3
Maize cobs biochar		-0.1 – 0.1
Miscanthus biochar	1.4 – 2.9 [b], 10	-3.5 – -3.1, -1 – -1.2, -0.6
Paper sludge biochar	1.1 [a, b]	-0.7
Pig manure biochar		-0.4
Poplar biochar	16	-1.2
Poultry litter biochar	1.1 [a, b]	-0.5, -0.2
Rice biochar		-0.4
Sewage sludge biochar	1.8 [a, b]	-0.8
Sugarcane biochar		-0.2
Switch grass biochar	1.5 [a], 11	-2.8 – -2.5, -0.4 – 0
Wheat straw biochar	1.1 –2.2 [b], 8.3	-2.1– -1.9, -0.9 – -0.7, -0.7
Whisky draff biochar	1.1 [a, b]	-0.8
Wood waste biochar	2.1 [a, b]	-1.3, -0.2
Yard waste biochar	3 [a]	-0.9

[a] Estimated from figure, [b] Produced energy.

It is important to note that almost all of the studies reported negative values for GWP associated with biochar production due to carbon abatement ability of biochar, with average emissions calculated as -0.9 kg CO_2eq/kg, as compared to 6.6 kg CO_2eq/kg for activated carbon. The average energy demands of biochar and activated carbon production were found to be 6.1 MJ/kg and 97 MJ/kg, respectively, indicating an order of magnitude difference between the two materials.

3.1.1 Adsorption capacity of biochar and activated carbon

In order to analyze the effects of numerous variables, adsorption capacities of biochar and activated carbon for various adsorbed materials were presented in Table A1 together with particle size, surface area, pH, contaminant concentration, adsorbed material and dose, and contact time reported in each study.

When compared on a per mass basis as in Table A1, adsorption capacity of biochar to remove cadmium and copper from water were in general found to be higher than those of activated carbon, whereas a significant difference could not be observed for chromium. Other heavy metals presented mixed results. However, data frequently included large reported ranges for adsorption capacity, thereby eliminating the possibility of making statistically significant conclusions. Adsorption capacity of biochar ultimately depends on multiple factors including the type of raw material used. While careful selection of one type of biochar may provide superior adsorption performance over activated carbon, another type of biochar may have just the opposite effect. Similarly, particle size, surface area, pH, contaminant concentration, adsorbed material and dose, and contact time are other factors that need to be considered.

A sensitivity analysis was conducted based on physical properties and experimental data reported in Table A1. The effects of the following factors were investigated: particle size; surface area; pH; contaminant concentration; adsorbent dose; and contact time. Among these, surface area provided a reasonable degree of correlation with adsorption capacity, and its influence was further investigated and results presented in Figure 1. While a positive correlation was observed between surface area and adsorption capacity for chromium, zinc, and lead, a clear positive correlation could not be observed for cadmium and copper based on data surveyed through literature. In fact, data through existing literature suggests that adsorption capacity of cadmium and copper tend to decline as surface area increases. However, high adsorption capacities reported at relatively small surface areas may indicate underlying mechanisms that may be equally effective in determining adsorption. Some studies indicate that adsorption capacity of biochar depend on ion exchange as the dominating mode by which biochar adsorb metal ions rather than physical properties of the adsorbent (Mohan et al. 2007; Tong et al. 2011; Xu et al. 2013).

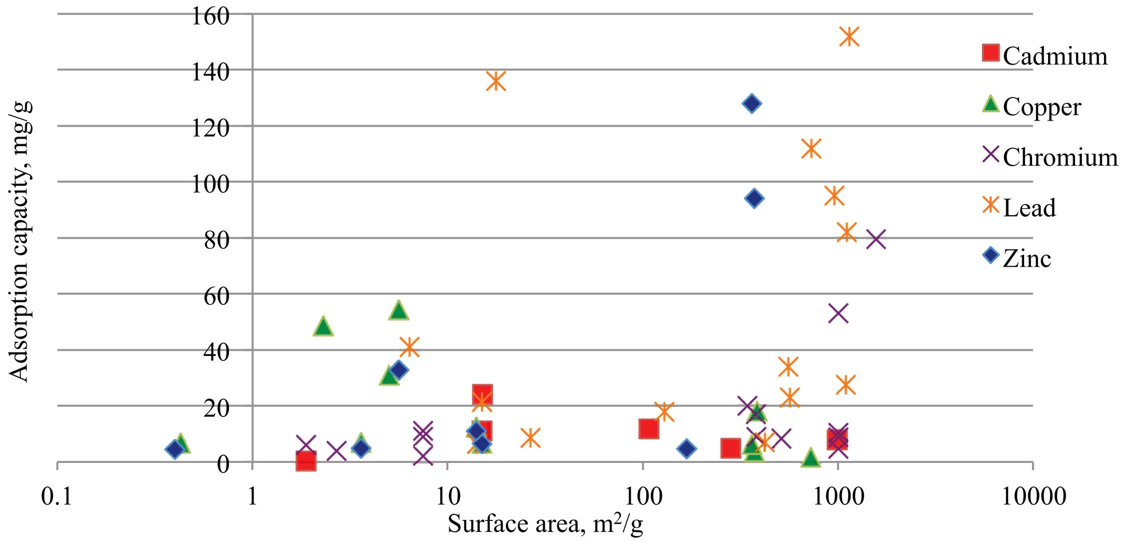


Figure 1. The effect of surface area on adsorption capacity of biochar to adsorb select heavy metals. A logarithmic scale was used for the x-axis corresponding to surface area. Where a positive correlation was observed for Chromium, Lead, and Zinc, no clear correlation was observed for Cadmium and Copper.

When adsorption of heavy metals by biochar and activated carbon are compared on a per mass of adsorbent basis, results indicate that adsorption capacity of biochar can compete with or exceed activated carbon for contaminants analyzed. However, a raw material that outperformed the other in all categories could not be found. Therefore, if faced with a choice between activated carbon and biochar, the answer would lie in understanding the intended use; the intended contaminant or the mix of materials to be adsorbed. Engineered systems to adsorb contaminants could then be optimized by selecting raw materials that perform best in each category.

3.1.2 Evaluating environmental impact of biochar as adsorbent compared to activated carbon

As the main goal of adsorbent materials are to remove contaminants, heavy metals in this case, an appropriate functional unit for the comparison of environmental impact of biochar and activated carbon would be impacts per mass of contaminant removed, rather than impacts per mass of adsorbent material. Therefore, the two metrics of MJ/kg contaminant, and kg CO_2eq/kg contaminant were used to compare the two materials. Statistical distributions combined with a Monte Carlo analysis yielded the results presented in Figures 2 and 3 together with the indicated 95% confidence interval.

Figure 2 indicate that the energy demand for biochar is significantly lower than activated carbon for most heavy metals. Only in the case of lead adsorption, the figure illustrates that the difference in confidence intervals is not large enough to warrant a clear answer.

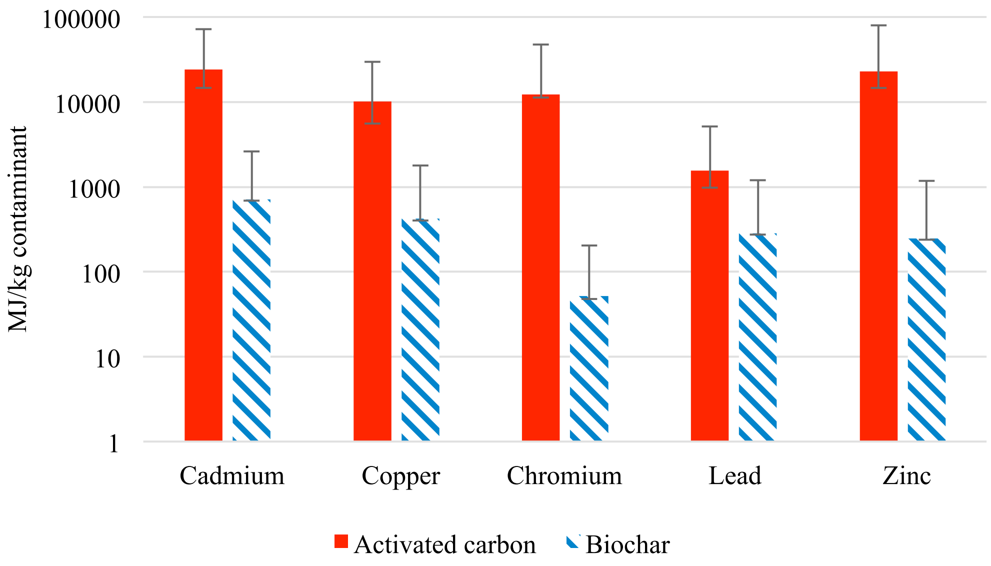


Figure 2. Energy demand for adsorption of heavy metals by biochar and activated carbon. Bars indicate the mean, and the error bars indicate the 95% confidence interval of results.

Results of analysis presented in Figure 3 illustrates that GHG emissions resulting from adsorption of heavy metals by activated carbon are higher than GHG emissions of biochar. The differences were found to be statistically significant. It is interesting to note that biochar has a negative emissions value for all the heavy metals studied due to its ability to sequester carbon.

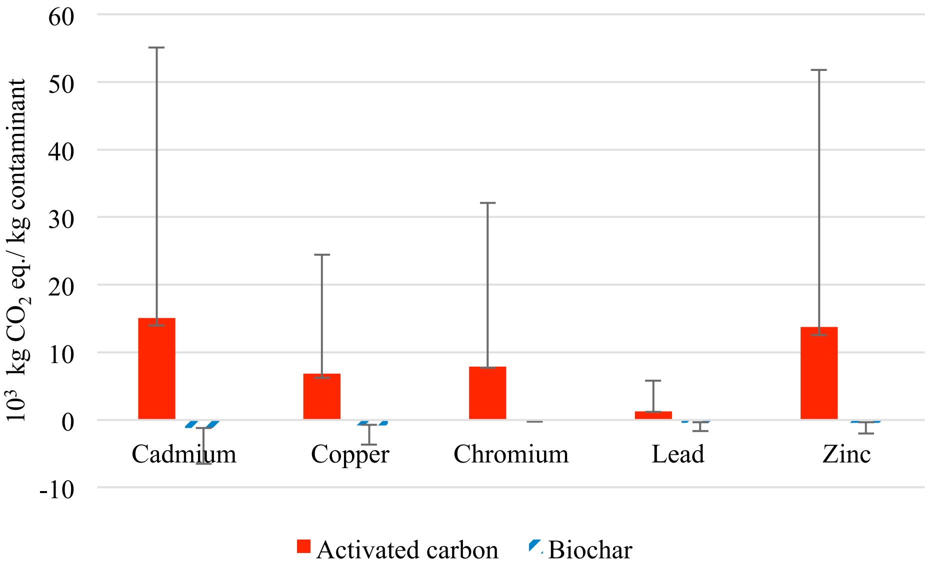


Figure 3. Greenhouse gas emissions resulting from adsorption of heavy metals by biochar and activated carbon. Bars indicate the mean, and the error bars indicate the 95% confidence interval of results.

While energy required to produce activated carbon is many times more than the energy demand to produce the same amount of biochar, typically, spent activated carbon is not disposed of but regenerated for reuse. It was deemed necessary to factor this life cycle stage into the analysis. Regeneration process was reported to require about 50% of the energy demand of activated carbon during its production. It is important to note that activated carbon loses about 10% of its weight during each regeneration process (Muñoz et al. 2007).

Energy required to regenerate activated carbon was compared with the energy demand for biochar production based on the adsorption capacity to remove heavy metals. In the case of copper for example, activated carbon needs to be regenerated twice before biochar would be replaced and discarded due to the higher adsorption capacity of biochar to remove copper.

Energy demand distributions for activated carbon and biochar that were setup based on data points presented in Table 1 were used to test the impact of regeneration on results. The average energy demand in MJ/kg adsorbent, and a 95% confidence interval were used to compare results. Figure 4 illustrates that energy demand of biochar is not expected to meet or exceed energy demand of activated carbon for copper adsorption even when the regeneration capabilities of activated carbon is taken into account. Similar results were obtained for the other heavy metals analyzed, where energy demand of biochar was not expected to match the energy demand of activated carbon.

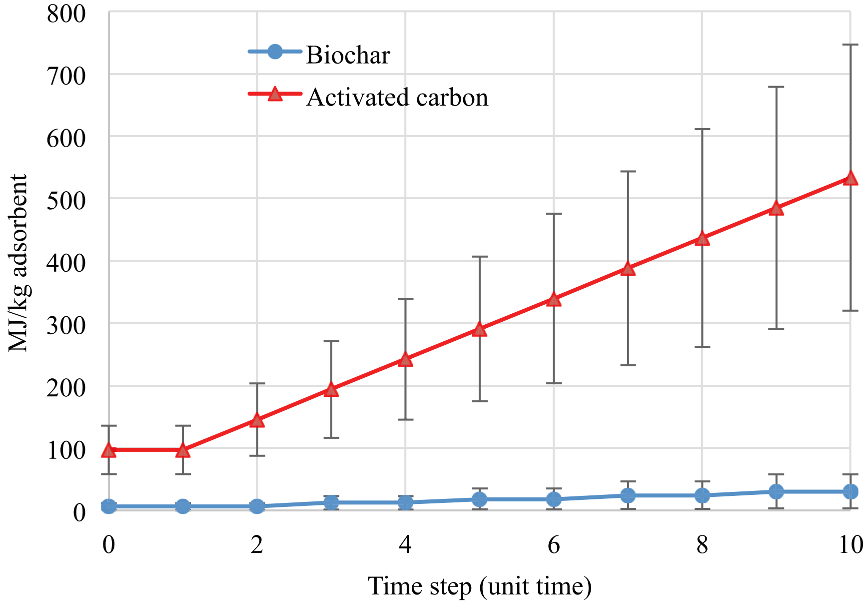


Figure 4. Energy demand to produce and regenerate biochar and activated carbon for copper adsorption. Error bars indicate the 95% confidence interval for results.

3.2 Economic performance of biochar as an adsorbent compared to activated carbon

The economic performance of biochar and activated carbon when used as a sorbent were compared as part of the study. Their performances were evaluated based on adsorption capacity and current commercial price of each material to calculate effective adsorption cost. Biochar produced from different raw materials were analyzed separately.

3.2.1 Biochar density

Market prices of biochar were either reported by mass or by volume by commercial companies. The unit discrepancy required an additional density calculation to convert volume to mass, to compare prices and feasibility of different alternative materials to be used as an adsorbent in units of \$/kg. Bulk density of biochar ranged between 0.1-1.1 Mg/m^3 based on 20 datapoints as shown in Table 2 (Anderson et al. 2013; Beesley and Marmiroli 2011; Berger 2012; Downie 2011; Mahimairaja 2012; Mohan et al. 2011; Nhuchhen et al. 2014; Shackley et al. 2010). Data were analyzed statistically and a triangular distribution with a mean of 0.47 was fitted to the dataset. The mean value of 0.47 Mg/m^3 was also used to represent the density of biochar in this study to convert unit volume to unit mass.

Table 2. Density of biochar produced from different raw materials

Biochar Type	**Density, Mg/m^3**	**Source**
Switch grass	0.11	(Nhuchhen et al., 2014)
Forest residues	0.16	(Anderson et al., 2013)
Mill residues	0.16	(Anderson et al., 2013)
Raw pine	0.16	(Nhuchhen et al., 2014)
Balsa	0.16*	(Downie, 2011)
Sweet gum	0.18	(Nhuchhen et al., 2014)
Chopped salix biochar	0.27	(Berger, 2012)
Redwood	0.3*	(Downie, 2011)
Biochar	0.3	(Beesley and Marmiroli, 2011)
White pine	0.35*	(Downie, 2011)
Different woods	0.36	(Downie, 2011)
Biochar	0.4	(Shackley et al., 2010)
Basswood	0.4*	(Downie, 2011)
Biochar	0.45	(Mahimairaja, 2012)
Oak bark	0.57	(Mohan et al., 2011)
Red oak	0.6*	(Downie, 2011)
Hard maple	0.6*	(Downie, 2011)
Biomass	0.77	(Nhuchhen et al., 2014)
Oak wood	0.91	(Mohan et al., 2011)
Lignum vitae	1.1*	(Downie, 2011)

*Estimated from figure

3.2.2 Unit price of biochar and activated carbon

A realistic evaluation of the cost of biochar and activated carbon used as a sorbent required commercial price of products to be used together with their adsorption capacity to estimate the cost of adsorbing a given amount of contaminant or material. Current biochar prices were collected through companies in different countries and converted to US$/kg, together with a few data points from published literature. The commercial price of biochar ranged between $0.8 – 18/kg based on 14 data points, as presented in Table 3. It is interesting to note that biochar prices obtained from literature were significantly lower than commercial prices, where literature reported values as low as $0.05/kg, and hence were excluded from the study. Activated carbon prices obtained from literature and commercial sources ranged between $0.34-22/kg based on 13 data points. The average cost of activated carbon and biochar were calculated to be $5.6 and $5, respectively. The standard deviation was calculated as 7.5 for price of activated carbon, and 5.26 for price of biochar. International Biochar Initiative, a non-profit organization dedicated to promoting biochar research and commercialization, report biochar price to be $3.08/kg in 2014 based on the average cost of 56 products (IBI, 2014). While further detailed information on the types of biochar or the distribution of values were not available, comparing the confidence interval calculated in this study to their reported value provides further credence to the range of results presented in this study.

A hypothesis test carried out to test whether there was a significant difference in the average price of biochar and activated carbon concluded that there was not sufficient evidence to prove that the average prices were significantly different at the 95% confidence interval.

Table 3. Unit price of biochar and activated carbon. Commercial prices reflect 2015 prices in US Dollars. (Alibaba.com, 2015; Amazon.com, 2015; Babel and Kurniawan, 2004; Gaunt and Lehmann, 2008; Grassi et al., 2012; Johnsen et al., 2016; Mohan et al., 2011; Rasmussen, 2011; Slaughter, 2011)

Material Type	Location	US$/kg
Activated Carbon (granular)	N/A	6.4
Activated carbon (Coconut shell charcoal oxidized with nitric acid)	N/A	0.3
Activated carbon (Commercial)	N/A	21
Activated carbon (Coconut shell)	N/A	2.2
Activated carbon (Coconut shell charcoal)	N/A	0.3
Activated carbon (Coconut shell)	China	1.5-3
Activated carbon (Commercial oxidized with nitric acid)	N/A	1.4
Activated carbon (Commercial type Filtrasorb-400)	N/A	20-22
Activated carbon (Commercial)	N/A	1.4
Activated carbon (Granular)	N/A	2.2
Activated carbon (Granular)	Oklahoma	3.2
Activated carbon (Powdered)	Oklahoma	1.2-2
Activated Carbon (Granular, Coconut)	Illinois, USA	9.2
Bamboo biochar	Alabama, USA	7*
Coconut shell biochar	USA	0.8
Coppiced hardwoods biochar	UK	1.6
Corn debris, manure, and forestry debris (activated biochar)	Idaho, USA	2*
Corn debris, manure, and forestry debris (raw biochar)	Idaho, USA	1.5*
Hardwood biochar	Australia	2.3*
Mixed hardwood and softwood biochar	Central Canada	1*
Pinewood biochar	Missouri, USA	0.9
Pinewood biochar		0.9-1.9
Pinewood biochar (Organic conifer biomass)	Oregon, USA	8.3*
Softwood chips Biochar	California USA	3.5
Softwoods mix with Pine, Spruce, Fir and Cedar biochar	Vermont, USA	7.2*
Tree branches biochar	Kansas, USA	11
Virgin wood feedstock biochar	Massachusetts, USA	17.8

* Product sold by volume rather than mass - conversion to $/kg according to calculated mean density of 0.47 Mg/m^3

3.2.3 Economic performance of biochar and activated carbon when utilized as an adsorbent

One of the main goals of the study was to compare the economic performance of biochar and activated carbon when used as an adsorbent, rather than costs per mass or volume. Therefore, economic performance of materials as an adsorbent were evaluated by analyzing adsorption capacity of the alternatives and their commercial prices.

Economic analysis included defining and evaluating distributions to seek overall trends in performance, rather than investigate a specific adsorbent or raw material used. Monte Carlo simulation was used to estimate and compare the cost of heavy metal adsorption by biochar and activated carbon. A representative outcome was presented in Figure 5, where adsorption cost to remove copper is being displayed. Results indicate that a significant difference between biochar and activated carbon does not exist to adsorb a unit mass of copper. The result was further supported by Figure 6, which presents the mean values of the distributions together with a 95% confidence interval. In the case of copper, both mean values fall at around $600/kg copper and the range of results seem to overlap, indicating a significant difference was not expected.

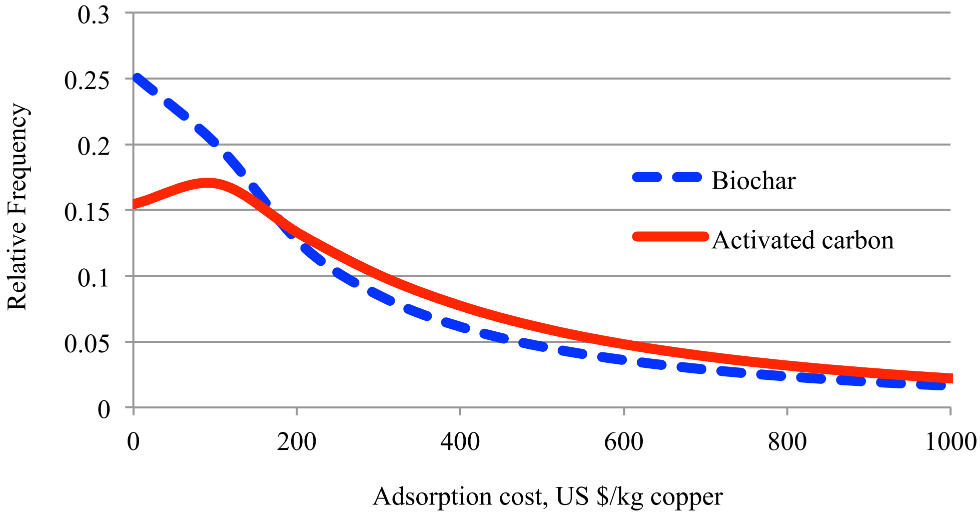


Figure 5. Adsorption cost distribution for copper removal using biochar and activated carbon. Results indicate that a significant difference between biochar and activated carbon does not exist to adsorb a unit mass of copper.

Similarly for adsorbing lead, Figure 6 indicates that biochar, on average, is likely to be more expensive than activated carbon as the means of the distributions were $300/kg lead for biochar and $180/kg lead for activated carbon. The confidence intervals also indicate a near overlap, thereby supporting the conclusion that the two materials perform comparably.

A significant difference is noted for the adsorption cost to remove zinc, where biochar cost lower than activated carbon. The difference was apparent in the calculated mean values of $200/kg and $1240/kg for biochar and activated carbon, respectively, and as there was no overlap of the confidence intervals indicating statistical significance. In this case, it can be concluded that adsorption cost to remove zinc was lower for biochar than activated carbon.

Figure 6 also indicates a similar, but larger difference between the adsorption cost to remove chromium. Beyond a difference in their mean values of $40/kg and $500/kg for biochar and activated carbon, respectively, the range of results do not overlap at the 95% confidence interval. Similar to the case for zinc, it can be concluded that adsorbing chromium by biochar could be economically advantageous than using activated carbon.

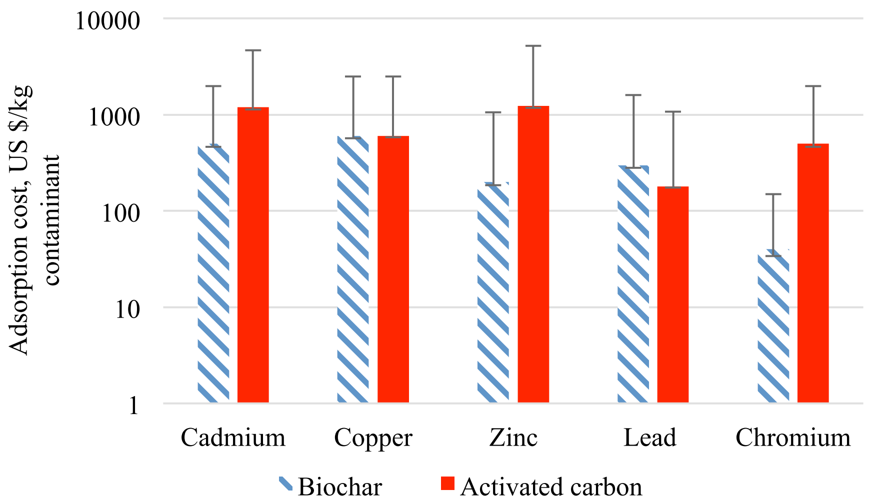


Figure 6. The cost of adsorbing heavy metals by biochar and activated carbon. Bars indicate the mean, and the error bars indicate the 95% confidence interval of results.

Biochar is an effective biosorbent due to its efficiency in removing a variety of materials from aqueous solutions, both in terms of technical and economic performance. In adsorption performance comparison, biochar was generally found to be less costly than activated carbon to remove different adsorbed materials. However, the ultimate decision on alternative materials must be evaluated on a case by case basis, based on the availability of types of biochar from different raw materials, as well as the contaminant or material mix to be adsorbed.

Results presented in this section were intended to identify general trends in the comparative economic performance of biochar and activated carbon for adsorption. Uncertainty introduced by variations in biochar properties and the varying nature of market prices for commercial products should be kept in perspective while extrapolating results presented here.

3.3 Impact of long distance trade on environmental performance of biochar

Another goal of the study was to assess the environmental impacts resulting from long distance or international trade of biochar. The impact of international trade on biochar was evaluated based on GHG emissions and energy demand to transport biochar via land or waterways. The aim of this step of the analysis was to identify the magnitude of impact caused by long distance transportation, rather than precisely calculate impacts, which could only be possible when the origin, destination, and mode of transportation were known. The environmental impact of international trade was quantified to compare with impacts deriving from the production phase. In other words, would the environmental performance of biochar still be better than activated carbon even when the former was obtained internationally over long distances and the latter obtained locally.

Estimate distances between 15 locations, representative of every continent, region, or major biochar company locate during this study were used, as exact numbers can only be determined when there are specified buyers and sellers. Such distances represent the distance from the center of a city or state to the center of the other location. Among modes of transportation, truck was chosen over rail as its energy demand and environmental impacts are higher, thereby resulting in a worst case scenario. Waterborne transportation was assumed for intercontinental shipments. Distance between two locations, energy consumption, and GHG emissions resulting from the modeled transportation are presented in Tables B1-3.

International trade of biochar was found to slightly affect its environmental performance, but the gap is still large when compared to the impact resulting from the production of activated carbon. Thus, the potential increase in energy consumed resulting from long distance or international trade is about 35% of the energy demand to produce 1 kg of biochar. In terms of GHG emissions, long distance trade eliminates the role of biochar to sequester carbon, hence the average emissions value of -0.9 kg CO_2eq/kg would become zero. Still, biochar was found to have lower GHG emissions than activated carbon when transported between selected locations.

Results indicate that biochar may be shipped several times around the globe before balancing the impact resulting from production and activation of activated carbon. Activated carbon would become favorable in terms of GHG emissions if it were obtained locally and biochar were transported more than 40,200 km over land by trucks or more than 274,000 km over waterways. Considering that the Earth's circumference is about 40,000 km, transporting goods over such distances may not be necessary or practical.

3.4 Barriers that may prevent biochar to replace activated carbon in adsorption applications

Today, activated carbon is the most common adsorbent used. Results of this study, however, indicate that activated carbon may not always be the most effective, nor the least costly option for adsorption purposes. For certain materials and contaminants, biochar on average proved to have comparable or better adsorption capacity and improved economic performance. There is some literature discussing the potential application of biochar for water treatment purposes, but no major commercial applications exist yet. There are real or perceived barriers that needs to be resolved before biochar may be expected to replace activated carbon such as:

- Although biochar removes some contaminants more effectively than activated carbon, the adsorption efficiency of biochar is not stable but fluctuates, whereas activated carbon has a more stable and predictable efficiency (Berger 2012).
- Biochar may take longer than activated carbon to adsorb contaminants when same amounts of the two materials are used (Oleszczuk et al. 2012). This may lead to either a need for larger amounts of biochar to have equivalent process time or longer time to adsorb the same amount of contaminant. The former would increase costs, and the latter may pose challenges in time-constrained applications.
- There is a lack of consistent and comprehensive data on the performance of biochar. The differences in performance of biochar made from different raw materials complicate the issue.

Using biochar as an adsorbent is a relatively new approach. Findings of this study indicate that biochar can be used as an alternative to activated carbon for certain applications. There is evidence that biochar, if engineered correctly for the task, could be at least as effective as activated carbon, at a lower cost. However, there are still technical barriers preventing its widespread implementation. Further research along identified areas could return significant environmental, economic, and societal benefits.

4. Conclusion

The main goal of the study was to conduct a meta-analysis to evaluate the environmental and economic performance of biochar in comparison to activated carbon. The impact long distance trade would have on environmental impacts of biochar were also investigated as part of the study. A discussion on some of the barriers that prevent the use of biochar adsorption applications was also presented.

Due to a lack of data regarding full environmental impacts of biochar from LCA studies, the environmental focus of the study was mainly on the most commonly reported environmental impacts of energy demand and GWP. Data in these categories indicate that biochar has lower environmental impact than activated carbon. For GHG emissions, biochar on average was found to have negative emissions of -0.9 kg CO_2eq./kg due to its ability to sequester carbon, while activated carbon demonstrated higher on average GHG emissions of 6.6 kg CO_2eq./kg. The average energy consumption to produce 1 kg of activated carbon and biochar was calculated to be 97 MJ/kg and 6.1 MJ/kg, respectively.

An evaluation of the economic performance of biochar and activated carbon demonstrated that the average cost of activated carbon and biochar were \$5.6/kg and \$5/kg, respectively. These unit prices however, need to be combined with adsorption capacities to yield information on the cost of contaminant removal. The adsorption cost of biochar was lower than activated carbon to remove chromium and zinc with a 95% confidence. Adsorption cost for lead and copper were found to be comparable, and results cannot be generalized as the type of biochar and its price could take results both ways and therefore more specific testing is recommended.

The environmental impact resulting from long distance transportation of biochar was assessed. While results demonstrate that long distance trade of biochar could affect its environmental impacts somewhat, the gap is still large when compared to activated carbon production. Transportation distances required to overturn this conclusion were not practical. These results indicate that biochar would still have less environmental impact than activated carbon even if it were transported over long distances.

Obstacles that may prevent application of biochar as a replacement to activated carbon were also discussed within the study. Among these reasons, variations in material property, especially variations due to use of different raw materials are major hindrances. Still, engineered products that contain a mix of different types of biochar may be optimized for adsorption applications.

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Appendix A

Table A1. Adsorption capacity of biochar and activated carbon produced from different raw materials. Products have been grouped based on adsorbed materials to ease comparison of adsorption capacity.

Adsorbent	Particle size of adsorbent, mm	Surface area, m^2/g	pH	Contaminants concentration, mg/l	Adsorbent dose, g/l	Contact time, hour	Adsorbed material	Adsorption capacity, mg/g	References
Switchgrass via hydrothermal carbonization biochar	> 0.045	2.11	5	40	2	24	Cd	1.5	(Regmi et al., 2012)
Activated biochar	> 0.045	5.01	5	40	2	24	Cd	34	
Powdered activated carbon	0.044-0.149	726	5	40	2	24	Cd	1.5	
Dairy manure-derived biochar	0.5	5.61		562		10	Cd	51.4	(Mohan et al., 2007; X. Xu et al., 2013)
Oak bark biochar	0.25-0.6	25.4	8.2	0.125		24	Cd	5.4	
Pine bark biochar	0.25-0.6	1.88	8.2	0.125		24	Cd	0.34	
Granular activated carbon	0.25-0.6	984	8.2	0.125		24	Cd	8	
Cord grass biochar	< 0.25	15.1	5				Cd	5.7 - 42.5	(Harvey et al., 2011; Kuo et al., 2008)
Loblolly pine biochar	< 0.25	281	5				Cd	2.92- 6.97	
Honey mesquite biochar	< 0.25	107	5				Cd	5.5- 18	
Pig manure chemically treated biochar	0.42-0.6	15	5	11-281	5		Cd	11.2	(Kołodyńska et al., 2012)
Peanut straw biochar	0.048		5	157- 790	2		Cu	89	(Tong et al., 2011)
Soybean straw biochar	0.048		5	157- 790	2		Cu	52.7	
Canola straw biochar	0.048		5	157- 790	2		Cu	37.5	
Activated carbon	0.048		5	157- 790	2		Cu	11.4	
Rice husks hydrothermal biochar	< 0.5		5-6		5-12.5	2-4	Cu	1.09	(Pellera et al., 2012)
Rice husks biochar (pyrolysis)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	0.02 - 2.9	
Olive pomace biochar (hydrothermal)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	0.6	
Olive pomace biochar (pyrolysis)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	0.17 - 1.3	
Orange waste biochar (hydrothermal)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	2.03	
Orange waste biochar (pyrolysis)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	0.08 - 1.4	
Compost biochar (hydrothermal)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	3.8	
Compost biochar (pyrolysis)	< 0.5		5-6	20-50	5-12.5	2-4	Cu	2.4 - 3.6	
Spartina alterniflor biochar	< 0.3	2.3	6	290	3.3		Cu	48.5	(Li et al., 2013)

Adsorbent	**Particle size of adsorbent, mm**	**Surface area, m^2/g**	**pH**	**Contaminants concentration, mg/l**	**Adsorbent dose, g/l**	**Contact time, hour**	**Adsorbed material**	**Adsorption capacity, mg/g**	**References**
Softwood biochar	> 0.0002	362	4.8		10	24	Cu	1.6- 11	(X. Chen et al., 2011)
Activated carbon	> 0.0002	383	4.8		10	24	Cu	6.3-30.2	
Hardwood biochar	< 0.5	0.43	7	63	5	24	Cu	6.8	
Corn straw biochar	< 0.5	13.98	5	63	5	24	Cu	12.5	
Switchgrass via hydrothermal carbonization biochar	> 0.045	2.11	5	40	2	24	Cu	4	(Regmi et al., 2012)
Activated biochar	> 0.045	5.01	5	40	2	24	Cu	31	
Powdered activated carbon	0.044-0.149	726	5	40	2	24	Cu	1.8	
Pig manure chemically treated biochar	0.42-0.6	15	5	6.3-157	5		Cu	6.8	(Kołodyńska et al., 2012)
Dairy manure-derived biochar	0.5	5.61		317		10	Cu	54.4	(Xu et al., 2013)
Oak wood biochar	0.25-0.6	2.73	2	1-100			Cr VI	3.03 - 4.9	(Mohan et al., 2011)
Oak bark biochar	0.25-0.6	1.88	2	1-100			Cr VI	4.6 - 7.5	
Activated carbon derived from coconut fibers		343	2	1-100			Cr VI	16 - 24	
Activated carbon derived from coconut shells		378	2	1-100			Cr VI	1.4-32.6	
Activated carbon derived from acid-treated coconut fibers		512	2	1-100			Cr VI	1.1 - 15.6	
Activated carbon derived from acid-treated coconut shells		380	2	1-100			Cr VI	1.6-16.4	
Activated carbon fabric cloth		1565	2	1-100			Cr VI	42.1 - 117	
Commercial activated carbon	0.5-2.36	1000	6	5-25			Cr VI	4.7	(Babel and Kurniawan, 2004; Mohan et al., 2011)
Commercial activated carbon oxidized with sulfuric acid	0.5-2.36	1000	6	5-25			Cr VI	8.9	
Commercial activated carbon oxidized with nitric acid	0.5-2.36	1000	6	5-25			Cr VI	10.4	
Coconut shell activated carbon	0.42-1.70	5-10	6	5-25			Cr VI	2.2	
Coconut shell charcoal coated with chitosan activated carbon	0.42-1.70	5-10	6	5-25			Cr VI	3.7	
Coconut shell charcoal Oxidized with sulfuric acid activated carbon	0.42-1.70	5-10	6	5-25			Cr VI	4.1	
Coconut shell charcoal oxidized with sulfuric acid and coated with chitosan	0.42-1.70	5-10	6	5-25			Cr VI	9	

Adsorbent	**Particle size of adsorbent, mm**	**Surface area, m^2/g**	**pH**	**Contaminants concentration, mg/l**	**Adsorbent dose, g/l**	**Contact time, hour**	**Adsorbed material**	**Adsorption capacity, mg/g**	**References**
Coconut shell charcoal oxidized with nitric acid activated carbon	0.42-1.70	5-10	6	5-25			Cr VI	11	
Commercial activated carbon type Filtrasorb-400		1000	2	100			Cr VI	53.2	(Babel and Kurniawan, 2004)
Waste tire activated carbon			2	100			Cr VI	58.5	
Rice husk activated carbon			2-3	300			Cr VI	45.6	
Coconut tree sawdust activated carbon	0.125-0.250	5-10	3	20			Cr VI	3.5	(Babel and Kurniawan, 2004; Selvi et al., 2001)
Sugar beet tailing biochar							Cr VI	123	(Dong et al., 2011; Suguihiro et al., 2013)
Banana Peduncle Biochar	≤ 0.1		2		2	24	Cr VI	114	(Karim et al., 2015)
Anaerobically digested sugarcane bagasse biochar	0.5–1	17.7		20	1.6	24	Pb	136	(Inyang et al., 2011)
Granular activated carbon	0.5–1	1100		20	1.6	24	Pb	81.9	
Sugarcane bagasse biochar	0.5–1	14.1		20	1.6	24	Pb	6.5	
Pinewood biochar	< 0.5		5	20	4	24	Pb	4.25	(Liu and Zhang, 2009)
Rice husk biochar	< 0.5		5	20	4	24	Pb	2.4	
Digested dairy waste biochar	0.5–1	555.2	5	20	2	24	Pb	33.5	(Inyang et al., 2012)
Digested whole sugar beet biochar	0.5–1	128.5	5	20	2	24	Pb	18	
Coconut shell activated carbon	1-2	728	5		4		Pb	112	(Issabayeva et al., 2006; Kobya et al., 2005; Momčilović et al., 2011; Song et al., 2014)
Coconut shell carbon (CSC-B) 2:1 (KOH/CSC) AC	1-2	1135	5		4		Pb	152	
Pine cone activated carbon		1094	5		2		Pb	27.5	
Palm shell activated carbon		957	5		5		Pb	95.2	
Apricot stone activated carbon		566	5		2		Pb	22.8	
Pig manure chemically treated biochar	0.42-0.6	15	5	20-517	5		Pb	21.4	(Kołodyńska et al., 2012)
Rice straw biochar	0.25	26.45	5				Pb	8.3-8.7	(Jiang et al., 2012)
Dairy manure biochar		6.4		207	5	4	Pb	41	(Cao et al., 2009)
Commercial activated carbon	0.15	421		207	5	4	Pb	7	
Switchgrass biochar	> 0.0002	3.6	4.8		10	24	Zn	0.33-9.6	(Han et al., 2013)
Hardwood biochar	> 0.0002	372.75	4.8		10	24	Zn	0.07-188	
Softwood biochar	> 0.0002	362.33	4.8		10	24	Zn	0.45-256	
Activated carbon	> 0.0002	167.8	4.8		10	24	Zn	0.20 - 9	
Pig manure chemically treated biochar	0.42-0.6	15	5	6.5-163	5		Zn	6.5	(Kołodyńska et al., 2012)

Adsorbent	**Particle size of adsorbent, mm**	**Surface area, m^2/g**	**pH**	**Contaminants concentration, mg/l**	**Adsorbent dose, g/l**	**Contact time, hour**	**Adsorbed material**	**Adsorption capacity, mg/g**	**References**
Dairy manure-derived biochar	0.5	5.61		327		10	Zn	32.8	(Xu et al., 2013)
Hardwood biochar	< 0.5	0.43	7.5	65	5	24	Zn	4.5	(X. Chen et al., 2011)
Corn straw biochar	< 0.5	13.98	8	65	5	24	Zn	11	

Appendix B

Table B1. Distance (km) between U.S. states and country capitals that were included in this study (Google Maps, 2015; Searates, 2015)

	U.K., London	**Nigeria, Abuja**	**Iraq, Baghdad**	**India, New Delhi**	**Germany, Berlin**	**France, Paris**	**China, Beijing**	**Canada, Ottawa**	**Brazil, Brasilia**	**Australia, Canberra**	**Washington D.C.**	**New York**	**Missouri**	**Florida**	**California**
California	340[a]; 14850[b]	910[a]; 16000[b]	910[a]; 20700[b]	1220[a]; 18500[b]	460[a]; 15800[b]	460[a]; 14700[b]	510[a]; 10350[b]	4190[a]	1470[a]; 14100[b]	600[a]; 12000[b]	4500[a]	4600[a]	3000[a]	4300[a]	-
Florida	160[a]; 8000[b]	720[a]; 10500[b]	700[a]; 17400[b]	990[a]; 17100[b]	260[a]; 8900[b]	240[a]; 7950[b]	290[a]; 18200[b]	3800[a]	1250[a]; 8970[b]	460[a]; 16400[b]	1500[a]	1800[a]	1900[a]	-	
Missouri	250[a]; 10300[b]	800[a]; 12700[b]	1250[a]; 19100[b]	1280[a]; 19000[b]	490[a]; 10850[b]	340[a]; 10200[b]	380[a]; 20200[b]	2900[a]	1350[a]; 11260[b]	560[a]; 18400[b]	1500[a]	1700[a]	-		
New York	5900[b]; 30[a]	590[a]; 9600[b]	580[a]; 15600[b]	15250[b]; 880[a]	6700[b]; 140[a]	5800[b]; 130[a]	19700[b]; 180[a]	1130[a]	1100[a]; 8900[b]	260[a]; 17900[b]	360[a]	-			
Washington D.C.	60[a], 6500[b]	640[a]; 9900[b]	640[a]; 16100[b]	940[a]; 15780[b]	190[a]; 7300[b]	180[a]; 6400[b]	220[a]; 19500[b]	1460[a]	1190[a]; 9160[b]	400[a]; 17700[b]	-				
Australia, Canberra	260[a]; 21200[b]	830[a]; 15500[b]	840[a]; 13700[b]	1330[a]; 11750[b]	480[a]; 22300[b]	380[a]; 2100[b]	430[a]; 9500[b]	530[a]; 20000[b]	1360[a]; 14500[b]	-					
Brazil, Brasilia	1130[a]; 9700[b]	1710[a]; 6540[b]	1730[a]; 15700[b]	1980[a]; 15060[b]	1280[a]; 10700[b]	1260[a]; 9600[b]	1300[a]; 21200[b]	1330[a]; 10600[b]	-						
Canada, Ottawa	220[a]; 5650[b]	750[a]; 10100[b]	740[a]; 15900[b]	1250[a]; 14880[b]	320[a]; 6400[b]	300[a]; 5550[b]	330[a]; 22100[b]	-							
China, Beijing	20300[b]; 180[a]	750[a]; 19600[b]	750[a]; 12200[b]	1060[a]; 10100[b]	320[a]; 21300[b]	300[a]; 20100[b]	-								
France, Paris	450[a]	700[a]; 8100[b]	700[a]; 12000[b]	1180[a]; 11280[b]	1680[a]	-									
Germany, Berlin	1100[a]	700[a]; 9180[b]	860[a]; 12700[b]	1150[a]; 12340[b]	-										
India, New Delhi	11800[b]; 880[a]	1640[a]; 13200[b]	1460[a]; 3000[b]	-											
Iraq, Baghdad	620[a]; 12100[b]	1170[a]; 14100[b]	-												
Nigeria, Abuja	580[a]; 8200[b]	-													
U.K., London	-														

[a]: Land transport (km)

[b]: Waterborne transport (km)

Table B2. Energy consumed to transport biochar between U.S. states and country capitals that were included in this study (MJ/ton biochar)

	U.K., London	Nigeria, Abuja	Iraq, Baghdad	India, New Delhi	Germany, Berlin	France, Paris	China, Beijing	Canada, Ottawa	Brazil, Brasilia	Australia, Canberra	Washington D.C.	New York	Missouri	Florida	California
California	2240	2710	3370	3230	2450	2290	1710	2310	2760	1990	2460	2550	1640	2380	-
Florida	1200	1850	2800	2910	1370	1230	2680	2100	1930	2530	810	1010	1030	-	
Missouri	1570	2200	3330	3340	1770	1600	3020	1610	2300	2860	820	940	-		
New York	840	1660	2480	2590	1010	870	2820	620	1860	2620	198	-			
Washington D.C.	940	1720	2590	2700	1120	980	2830	800	1920	2670	-				
Australia, Canberra	3090	2610	2370	2360	3350	3130	1550	3060	2760	-					
Brazil, Brasilia	1980	1850	3120	3170	2190	2020	3660	1460	-						
Canada, Ottawa	900	1810	2610	2750	1060	940	3250	-							
China, Beijing	2910	3130	2110	1970	3120	2960	-								
France, Paris	250	1500	2050	2220	920	-									
Germany, Berlin	600	1660	2230	2350	-										
India, New Delhi	2120	2730	1220	-											
Iraq, Baghdad	2020	2600	-												
Nigeria, Abuja	1450	-													
U.K., London	-														

Table B3. Greenhouse gas emissions resulting from international trade of biochar between U.S. states and country capitals that were included in this study (kg CO_2 eq./ton biochar)

	U.K., London	Nigeria, Abuja	Iraq, Baghdad	India, New Delhi	Germany, Berlin	France, Paris	China, Beijing	Canada, Ottawa	Brazil, Brasilia	Australia, Canberra	Washington D.C.	New York	Missouri	Florida	California
California	450	590	710	710	500	470	370	780	640	420	830	860	550	800	-
Florida	240	410	590	630	280	250	530	410	470	520	270	340	350	-	
Missouri	320	480	730	740	380	330	600	540	550	590	280	320	-		
New York	160	360	520	540	200	180	550	210	450	520	70	-			
Washington D.C.	180	380	540	590	230	200	550	270	460	540	-				
Australia, Canberra	610	560	520	550	680	620	330	620	630	-					
Brazil, Brasilia	470	490	730	760	520	490	800	520	-						
Canada, Ottawa	190	400	550	620	230	200	640	-							
China, Beijing	570	650	460	460	620	580	-								
France, Paris	80	340	350	520	310	-									
Germany, Berlin	200	370	490	540	-										
India, New Delhi	470	650	350	-											
Iraq, Baghdad	430	590	-												
Nigeria, Abuja	320	-													
U.K., London	-														