Resources, Conservation and Recycling 118 (2017) 13–26

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Life cycle environmental and economic performance of biochar compared with activated carbon: A meta-analysis

Hashim A. Alhashimi, Can B. Aktas*

Department of Civil and Environmental Engineering, University of New Haven, West Haven, CT 06516, USA

ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form
17 November 2016
Accepted 20 November 2016
Available online 30 November 2016

Keywords:
Biochar
Activated carbon
Heavy metal adsorption
Environmental impact
Economic analysis
Transportation impact

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.

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 et al., 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; Chen et al., 2011a,b, 2008; 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; Zhang et al., 2013a,b).

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

* Corresponding author.
E-mail address: caktas@newhaven.edu (C.B. Aktas).

http://dx.doi.org/10.1016/j.resconrec.2016.11.016

from municipal wastewater as well as from industrial wastewater (Chen et al., 2011a,b; 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; Zhang et al., 2013a,b; 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