



Review

The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review



Mandu Inyang*, Eric Dickenson*

Applied Research and Development Center, Southern Nevada Water Authority, Henderson, NV 89015, United States

HIGHLIGHTS

- The potential role of biochar in water treatment systems was reviewed.
- The challenges and benefits of applying biochar in water treatment were presented.
- Biochar can potentially serve as a sustainable surrogate for activated carbon.

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ABSTRACT

In this work, the potential benefits, economics, and challenges of applying biochar in water treatment operations to remove organic and microbial contaminants was reviewed. Minimizing the use of relatively more expensive traditional sorbents in water treatment is a motivating aspect of biochar production, e.g., \$246/ton non-activated biochar to \$1500/ton activated carbon. Biochar can remove organic contaminants in water, such as some pesticides (0.02–23 mg g⁻¹), pharmaceutical and personal care products (0.001–59 mg g⁻¹), dyes (2–104 mg g⁻¹), humic acid (60 mg g⁻¹), perfluorooctane sulfonate (164 mg g⁻¹), and *N*-nitrosomodimethylamine (3 mg g⁻¹). Including adsorption/filtration applications, biochar can potentially be used to inactivate *Escherichia coli* via disinfection, and transform 95% of 2-chlorobiphenyl via advanced oxidation processes. However, more sorption data using biochar especially at demonstration-scale, for treating potable and reuse water in adsorption/filtration applications will help establish the potential of biochars to serve as surrogates for activated carbons.

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* Tel.: +1 (702) 856 3509 (M. Inyang), +1 (702) 856 3668 (E. Dickenson).

E-mail addresses: mandu.inyang@gmail.com (M. Inyang), eric.dickenson@snwa.com (E. Dickenson).

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1. Introduction

The contamination of water supplies by organic chemicals has continued to attract significant global attention from government regulatory agencies and the general public (Al-Mudhaf et al., 2009). Many organic compounds are persistent or can be biodegraded or transformed into recalcitrant products that survive conventional water treatment processes. Elevated concentrations of trace organic contaminants have already been reported in US tap waters (Benotti et al., 2009). The toxicity of some organic contaminants and potential adverse health effects associated with long term ingestion has been noted (Choi et al., 2013). But, the implementation of increasingly stringent environmental regulations compounded with growing potable reuse initiatives, has provided strong incentives to develop alternative, cost-effective and environmental-friendly technologies for treating organic contaminants (Qu et al., 2013b).

Biochar is a porous, carbon-residue derived from the thermal conversion of waste biomass under limited oxygen or anaerobic conditions. To date, there has been a growing body of literature on the application of biochar in water treatment (Jung et al., 2013; Kearns et al., 2014; Reddy et al., 2014; Inyang et al., 2014b). In particular, the use of biochar for the removal of persistent organic pollutants from aqueous systems has been documented (Liu et al., 2012; Zheng et al., 2013; Xie et al., 2014a; Chen et al., 2015). In some instances, stronger sorption and binding affinities of organic contaminants to biochar than commercial activated carbons were reported (Ahmad et al., 2012). Further, recent developments in biochar engineering using nanoparticles (NPs), and chemical, and biological modifications have yielded a novel class of hybrid-chars with huge potential for treating a wide array of organic contaminants (Inyang et al., 2014a).

Yet, practical use of biochar today remains largely restricted to land application. Accordingly, various aspects of biochar including its production, stability, physiochemical properties, and interaction mechanisms for soil management have been reviewed by several authors and compiled in the literature (Lehmann and Joseph, 2009; Beesley et al., 2011; Kookana et al., 2011). While, fewer studies exist that provide a review of biochar as a low-cost adsorbent for organic and microbial contaminants in water. Recently, the removal of organic contaminants from water by biochar was reviewed (Ahmad et al., 2014; Mohan et al., 2014; Xie et al., 2014b; Qian et al., 2015). Despite these reviews, knowledge on the practical application of biochar in water treatment operations, such as drinking water, potable, or municipal wastewater systems is limited.

The overarching objective of this work is to expand the current knowledge base on biochar application in water treatment by presenting a systematic review of current research findings on the sorption of organic and microbial contaminants by biochar, and examine the potential role of biochar in potable and reuse treatment systems. Specifically, this study will: (1) compare the sorptive characteristics of non-activated biochars with activated biochars or carbons from different thermochemical processes, (2) present the economics, benefits, and challenges of incorporating biochar sorbents into water treatment systems, (3) assemble data on the removal of microbial and organic contaminants from water by different biochars, and highlight removal mechanisms controlling their sorption processes, and (4) examine the modification or tailoring of biochars for specific water treatment operations.

2. Biochar or activated carbon?

Recently, biochar has been considered as a potential surrogate for activated carbon in environmental remediation and water treatment due to its low cost, relative abundance and comparative sorptive abilities (Kearns et al., 2014). Non-activated biochar, i.e., biochar that has not undergone any physical, chemical or biological modifications to improve its sorptive properties, can also be used as a precursor material for the production of activated carbon (Lima and Marshall, 2005; Girods et al., 2009). Thermochemical processes used in producing non-activated biochar and activated biochar or carbon are: gasification, slow pyrolysis, and fast pyrolysis. The physiochemical properties of biochars produced from each of these processes can vary and are mostly influenced by process conditions (reaction residence time and temperature), parent feedstock materials, and activation techniques. The products, yields and characteristics of non-activated and physically activated biochars or carbons derived from the different thermochemical processes are illustrated in Fig. 1.

Pyrolysis and gasification are thermochemical processes that produce biochar as a solid product, in addition to bio-oils and synthesis gas (Fig. 1). The process of slow pyrolysis however, favors a higher yield of biochar (30%) than fast pyrolysis (12%) or gasification (10%). Biochar can be produced from slow pyrolysis at moderate temperatures, 350–800 °C and residence times ranging from minutes to days (Fig. 1). Due to increased burn off of fixed carbon mass during pyrolysis, the surface areas and pore volumes of biochars generally increase with increasing temperatures and residence times (Zabaniotou et al., 2008). For example, increasing pyrolytic temperatures from 450 to 650 °C at 3 h residence time, increased the BET (Brunauer–Emmett–Teller) N₂ specific surface area (S_{BET}) of oak biochar from 2 to 225 m² g⁻¹ (Mukherjee et al., 2011). S_{BET} of swine manure biochar was also increased from 23 to 32 m² g⁻¹ when temperatures were increased from 350 to 700 °C at a holding time of 2 h (Zhang et al., 2013). High surface area and pore volumes of biochars can promote the retention of organic pollutants. However, animal waste biochars may have a lower S_{BET} than plant-based biochars produced at similar temperatures and residence times due to higher inorganic and ash constituents in most animal waste biochars (Sun et al., 2011b).

Below 600 °C, biochar from slow pyrolysis may retain their parent feedstock chemistry (Downie et al., 2009), however as pyrolysis temperatures increase above 600 °C, aliphatic groups such as phenols and carboxylic acids can be converted to neutral or fused basic aromatic groups (Mukherjee et al., 2011). Cao et al. (2010) found that swine manure biochar produced at 620 °C for 2 h did not retain the NCH and N–C=O groups originally present in the raw manure, but contained mostly aromatic or olefinic –C=C– groups. Polycyclic aromatic compounds such as dioxins and furans formed on slow pyrolysis-biochars at low temperatures (350–550 °C) and residence times < 1 h may be bioavailable and are more likely to be released when in solution (Hale et al., 2012). Pre-conditioning of such biochars by rinsing in methanol prior to applying them in water treatment has been reported (Jing et al., 2014) to remove leachable organic constituents from biochar and improve its sorption capacity. Fast pyrolysis mainly differs from slow pyrolysis in that it is performed at residence times < 2 s (Fig. 1). The resulting biochars may also be low in surface areas and pore volumes. Due to their short residence times, fast pyrolysis-biochars are suggested to retain more O-containing groups, e.g., phenolic, aromatic

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