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Biochar: production strategies, potential feedstocks and applications

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REVIEW ARTICLE

ABSTRACT

In recent years, biochar has been receiving increased research attention owing to its unique properties. Biochar is a stable carbon-rich by-product prepared from biomaterials through various heating methods. This paper provides an updated review on several aspects of biochar, including different methods of biochar production, available and alternative feedstocks and various applications of biochar. The key parameters controlling the property of biochar include type of heating method, residence time, heat transfer rate, and feedstock type. Biochar is usually produced through pyrolysis, gasification, torrefaction, flash carbonization and hydrothermal carbonization. Several types of feedstock has been proposed for biochar production and these include plant residues, wood chip, seaweeds, organic portion of municipal solid waste and animal manures. The potential biochar applications in agricultural and environmental aspects were studied as well. In addition, this review focuses on recent advances in biochar application such as its use as catalyst, fuel cells, supercapacitor and adsorbent.

KEYWORDS
biochar; carbon sequestration; climate change; fuel cells; soil fertility; sorption; biosorption

1. INTRODUCTION

Biochar is garnering significant attention in recent years as a significant tool for environmental management. Biochar is basically the charred by-product obtained during pyrolysis of biomass when the biomaterials are heated under nil/low oxygen conditions. Several investigators defined biochar in a variety of ways; of these, according to Lehmann and Joseph (2009), biochar is defined as “a carbon (C)-rich product when biomass such as wood, manure or leaves is heated in a closed container with little or unavailable air”. Biochar provides several environmental benefits and the most important ones include the potential of biochar to mitigate greenhouse gas emission and improve soil health (Marris, 2006). It has been observed that conversion of biomaterials into biochar results in renewable energy (bio-oil and synthetic gas) as well as decrease the content of CO_2 in the atmosphere (Lehmann, 2007; Renner, 2007). Application of biochar to soil enhances the properties and structure of soil, such as the organic matter content, soil pH, aeration condition, water retention capacity, cationic exchange capacity and the formation of aggregates of soil (Warnock et al., 2007, Atkinson et al., 2010). Biochar has also been reported to decrease the leaching losses of nitrogen and phosphorous in soil as well as the release of greenhouse gases (such as CH_4 and N_2O) from soil (Rondon et al., 2007; Amutio et al., 2013). Apart from these, specific properties of biochar including large specific surface area, porous structure, enriched surface functional groups (such as carboxyl, hydroxyl, carbonyl and phenolic hydroxyl groups) and mineral components make it possible to be used as proper adsorbent to remove pollutants from aqueous solutions (Tan et al., 2015). These properties are the important factors that influence the transformation, migration and bioavailability of contaminants in soil (Nartey and Zhao, 2014). Other applications include using biochar as a precursor for making catalyst electrodes of fuel cells, production of bioenergy and as a supercapacitor (Qian et al., 2015). However, it should

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be emphasized that these new high-value applications are still need to be explored, and further research and development is needed to reach conclusion.

Several types of feedstock has been proposed for biochar production and the suitability of each type of feedstock for biochar production is dependent on the nature, environmental, chemical composition as well as economic and logistical factors (Duku et al., 2011). On analysing elemental composition of biochar, Xu et al. (2013) found that biochar comprise of carbon (>60%), nitrogen, hydrogen, and some lower nutrient element (K, Ca, Na, Mg and Si). The properties of biochar play a vital role in deciding its application in various fields. For instance, properties such as high electrical conductivity, porosity and stability at lower temperatures prefer biochar to be used as electrodes material in microbial fuel cells (Huggins et al., 2014). Biochar with high structural bound nitrogen groups and porosity is favoured for the development of supercapacitors (Titirici et al., 2012). The presence of binding sites and high surface area in biochar will be useful to use it as adsorbent for various contaminants (Tan et al., 2015). In addition to these properties, low ash content of biochar may be preferred as soil amendments. Finally, biochar comprising relatively high structural bound oxygen groups is preferred in direct carbon fuel cells (Kacprzak et al., 2014).

Most of the reviews on biochar basically focus on economics and environmental aspects of using biochar as soil amendment. Other applications of biochar are seldom discussed and reviewed. Thus the objective of this review paper is to summarize overall benefits of biochar in various fields as well as production and characterization techniques.

2. BIOCHAR PRODUCTION

Biochar is usually produced via pyrolysis, gasification, torrefaction, flash carbonization and hydrothermal carbonization (Brown, 2009). Of these, pyrolysis is the most common and widely used method to produce biochar. Depending on the heating rate and residence time, two general types of pyrolysis exist: slow pyrolysis and fast pyrolysis. Slow pyrolysis involves heating the biomass at a low heating rate for a relatively long residence time. The heating process may sometimes proceed for several days and it is conventionally used for carbonization purposes. Slow pyrolysis often results in high yield of biochar, typically 35% biochar, followed by 30% bio-oil and 35% syngas (Nartey and Zhao, 2014). In contrast, fast pyrolysis involves heating the biomaterial at a high heating rate (usually 100-1000 ^{o}C/s) at a short residence time (few seconds). Fast pyrolysis usually favours high yield of bio-oil, but inhibit the formation of charcoal. It is estimated that through fast pyrolysis, a low yield of 12% biochar and 13% syngas and very high yield of 75% bio-oil can be expected. Pyrolysis conditions for biochar production (fast or slow pyrolysis), along with feedstock characteristics have a major influence on the physical and chemical properties (e.g. composition, particle and pore size distribution) of the final biochar. Pyrolysis reactors can be operated in batch and continuous modes. In most cases, continuous reactors are preferred and typical ones include fixed and fluidized-bed pyrolysers, auger/screw type pyrolysers and rotary kilns (Gwenzi et al., 2015). These reactors involve continuous input of feedstock and output of biochar, bio-oil and syngas, and often results in higher biochar yields and operational efficiencies than batch processes (Brown, 2009).

In gasification processes, biomaterials are primarily converted into gaseous mixture (syngas containing CO_2, CH_4, CO, H_2, etc.) by supplying a controlled amount of oxidizing agent under high temperature (greater than 700 °C) and atmospheric or elevated pressure. The oxidizing agent can be air, oxygen, steam or mixtures of these gases. In typical gasification process, the yields averages about 10% solid (biochar), 5% liquid (bio-oil) and 85% gas (syngas) (Nartey and Zhao, 2014). Hydrothermal carbonization basically occurs in water at elevated temperatures (160-800 °C); hence sometimes the char obtained refer as hydrochar. For hydrothermal carbonization process, the reaction pressure must be elevated (more than 1 atm) to maintain the water in a liquid form. Based on reaction temperature, hydrothermal carbonization (HTC) can be divided into high-temperature HTC (between 300 and 800 °C) and low-temperature HTC (below 300 °C) (Hu et al., 2010). Since hydrothermal carbonization requires water, this may be a cost-effective biochar production method for feedstocks with high moisture content (Titirici et al., 2012); and the resultant biochar often termed as hydrochar. It should be noted that the biochar produced by pyrolysis and hydrothermal carbonization varies widely in chemical and physical properties. It is generally accepted that typical biochar yields obtained by fast pyrolysis and gasification processes are significantly lower than that of slow pyrolysis and hydrothermal carbonization.

3. FEEDSTOCKS OF BIOCHAR

Biochar are usually produced from biomaterials, which are either regarded as waste, abundantly available or procured at low/nil cost. In particular, feedstocks of biochar production are mainly from agricultural biomass and solid wastes. These are abundantly available and sometimes cause nuisance and problems with disposal. For instance, converting invasive plant into biochar can improve the invasive plant management as well as solve disposal problems. On the other hand, seaweeds often reproduce fast and create nuisance in world oceans; hence their alternative usage such as production of biochar can be beneficial for local communities. In recent years, several feedstocks were recommended for production of biochar and these include plant residues (Yuan and Xu, 2011), wood chip (Kameyama et al., 2016), seaweeds (Park et al., 2016), organic portion of municipal solid waste (Li et al., 2015) and animal manures (Laird et al., 2010; Meng et al., 2014). It is important to understand that the type of feed stock strongly influences the properties of biochar and its further application. Sohi et al. (2010) reported that different feedstocks resulted in different magnitudes of surface area, pores and functional groups in biochars, and all these variables affect sorption characteristics of biochars. On the other hand, Zhao et al. (2013) studied the influence of feed stock on biochar properties by comparing twelve common organic residues, which include different animal manures, waste wood, crop residues, food waste, aquatic plants, and municipal waste. The results indicated that type of feedstock influenced biochar properties such as biochar C content, cation exchange capacity, fixed C, carbon sequestration capacity, mineral concentrations, and ash content. Therefore, optimizing biochar with desired characteristics for a specific application may require a careful selection of a feedstock.

4. APPLICATIONS OF BIOCHAR

4.1. Biochar as soil additive

Application of biochar to soil results in several benefits including mitigation of global warming by decreasing CO_2 emission from soil as well as improvement of soil health and productivity (Lehmann et al., 2011). Furthermore, biochar inhibit the release of N_2O and CH_4 from soil by both biotic and abiotic mechanisms. Rondon et al. (2005) reported a 50% reduction in N_2O emissions from soybean plots and almost complete suppression of CH_4 emissions from biochar amended acidic soils in the Eastern Colombian Plains. One of the reasons for the observed reduction of N_2O release from the soils may be that biochar promotes adsorption and retention of ammonium in soils and leads to the amounts of N available for denitrification reduced. Few investigators also reported reduction of NH_4 losses on addition of biochar to soils. During a pot trial with rice plants, Lehmann et al. (2003) found that the addition of fresh biochar reduced ammonium losses by 10%.

Biochar as an additive in soil attributes to increase in agricultural productivity owing to increase in soil fertility, water retention, soil cation exchange capacity, pH in acidic soils and enhanced soil microbial activity and nutrient retention (Lehmann et al., 2011). The water retention capacity of biochar generally ranges from 75 to 247% (Solaiman et al., 2012). This is an important advantage in best management practices such as green roofs. Githinji (2014) reported that biochar amendment had a positive impact on the soil. In particular, biochar decreased the bulk density of the soil leading to increased total soil porosity, which increased soil aeration, volumetric water content and water retention. The authors predicted that this would lead to enhanced plant growth as roots access sufficient moisture and oxygen. Biochar also contains N, P, K and other basic cations (Ca and Mg), which are essential plant nutrients. In addition, biochar increases soil fertility indirectly by increasing the potential of soil to retain nutrients. This is basically due to high cation exchange capacity of biochar which prevents soil nutrients from leaching through water and thereby providing a nutrient reserve available to plant roots. Cation exchange capacity of biochar range from 8 to 40000 $cmol_c$/kg has been reported and the values tend to increase over time after application to soil (Gwenzi et al., 2015). Applying 20 g/kg biochar to an agricultural soil mixed with swine manure biochar decreased the leaching of phosphate and nitrate by 69% and 11%, respectively (Laird et al., 2010). Due to this, biochar reduces eutrophication potential of surface water bodies by minimizing nutrient losses from soil (Laird et al., 2010). It should also be noted that carbon in biochar is highly recalcitrant in soils, with reported residence times in the range of 100-1000 years (Verheijen et al., 2009). Therefore, biochar incorporated in soil represents a potential terrestrial carbon sink and also a means of mitigating CO_2 emissions. Several investigators reported that biochar stimulate soil microbial activity (Xu et al., 2013) and increase fungi abundance and functioning. Owing to its highly porous structure and large surface area, biochar offers place for beneficial soil micro-organisms such as mycorrhizae and bacteria.

4.2. Biochar as adsorbent

It is well known that carbonaceous materials can be utilized as sorbents for organic as well as inorganic pollutants. Activated carbon is a proven and commercial sorbent, which is widely used in industrial wastewater schemes to decrease total dissolved solid concentrations. Being comprised of several functional groups, as well as possess large surface area and porous structure, biochar can be regarded as an alternative low-cost alternative adsorbent for activated carbon. It should be noted that preparation of activated carbon requires high temperature and additional activation process. On the other hand, production of biochar is comparatively cheaper with lower energy requirements (Cao et al., 2009; Tan et al., 2015). In addition to these, biochar comprise of non-carbonized fraction that may interact with soil pollutants (Ahmad et al., 2014). As stated by Uchimiya et al. (2011), the extent of O-containing hydroxyl, carboxyl, and phenolic surface binding groups in biochar play an important role to bind soil contaminants.

As discussed previously, sorption properties of biochar strongly depend on the chemical composition of feedstocks and the pyrolysis conditions (temperature and residence time). Pyrolytic temperature generally has significant influence on the surface functional groups of biochar as well as surface area (Antal and Gronli, 2003). Gai et al. (2014) investigated the effects of feedstock (wheat-straw, corn-straw and peanut-shell) and pyrolysis temperature (400, 500, 600 and 700 °C) on the characteristics of biochar and its adsorption ability towards ammonium and nitrate. The results showed that biochar yield and contents of nitrogen, hydrogen and oxygen decreased as pyrolysis temperature increased from 400 to 700 °C. Owing to its high cation exchange capacity of 38.3 cmol/kg, corn-straw-based biochar produced at 400 °C exhibited highest NH4 uptake capacity of 2.3 mg/g. Similarly, Jung et al. (2016) studied effect of pyrolysis temperature on properties and phosphate adsorption capability of biochar derived from Undaria pinnatifida root powder. The authors found that the chemical properties of the biochar were significantly affected by increasing the pyrolysis temperature. In particular, at pyrolysis > 400 °C, the properties of biochar gradually worsened due to the blockage of pores. In contrast, high pyrolysis temperature also favours adsorption such as the case of biochar as sorbent in soil. Kameyama et al. (2016) evaluated the dependence of pyrolysis temperature (400, 600 and 800 °C) and feedstock (wood chips, moso bamboo, rice husks, sugarcane bagasse, poultry manure and domestic wastewater sludge) on the nitrate adsorption properties of biochar. Results indicated that high pyrolysis temperature (800 °C), especially wood-based biochar exhibited highest nitrate adsorption.

Biochar performed well in sorption of heavy metals, nutrients, dyes, pesticides and other organic compounds. In the case of heavy metals, several removal mechanisms may found to play a significant and these include, ion exchange, electrostatic interaction, surface complexation physical adsorption and precipitation (Nartey and Zhao, 2014; Tan et al., 2015). Lu et al. (2012) suggested four different possible mechanisms involved during removal of Pb(II) ions by sludge-based biochar. The mechanisms include, electrostatic outer-sphere complexation (due to metal exchange with Na+ and K^+ available in the biochar), co-precipitation and inner-sphere complexation of metals (with organic matter and mineral oxides of the biochar), surface complexation (with active carboxyl and hydroxyl functional groups of the biochar) and precipitation (as lead-phosphate-silicate). Other studies also reported mechanisms such as ion exchange during sorption of Cu(II) onto red seaweed-derived biochar (Park et al., 2016); precipitation supplemented complexation with hydroxyl functional groups during sorption of Cd(II) and Pb(II) onto wood- and bark-derived biochar (Mohan et al., 2007); and electrostatic attraction and complexation with carboxyl and phenolic groups during sorption of Cr(VI) onto sugar beet tailing-derived biochar (Dong et al., 2011). It should also be noted that several factors influences the sorption of heavy metal ions onto biochar. These factors include physical and chemical properties of heavy metal ions (such as molecular weight, ionic radius and chemical speciation), properties of biochar (such as surface area, functional groups and pore structure), and the process parameters (such as solution pH, temperature, biochar dosage and initial heavy metal concentration). Readers are encouraged to refer to other reviews for information on adsorption process (Crini, 2006; Vijayaraghavan and Yun, 2008). Table 1 lists some of the important results of heavy metal sorption from solutions by various types of biochar.

Biochar showed good sorption capacity towards various nutrients such as nitrate (Zhang et al., 2012), phosphate (Jung et al., 2016), ammonium (Takaya et al., 2016), fluoride (Oh et al., 2012) and perchlorate (Fang et al., 2013) from aqueous solutions. Apart from these, the potential of biochar to retain nutrients in soil has been studied by few investigators (Ding et al. 2010; Uzoma et al., 2011). Biochar can retain and slowly release essential nutrients to soil in order to improve agricultural properties as discussed in Section 4.1.

Biochars has been studied for several organic contaminants such as pesticides (Zheng et al., 2010), dyes (Leng et al., 2015), polycyclic aromatic hydrocarbons (Devi and Saroha, 2015) and antibiotics (Yu et al., 2016). In general, desirable properties of biochar such as high surface area and micro-porosity favour sorption of organic pollutants from aqueous solution (Ahmad et al., 2014). In their review, Ahmad et al. (2014) pointed out that biochars produced at >400 °C are more effective for organic contaminant sorption because of their high surface area and micro-pore development. Chen et al. (2008) predicted that the partitioning of organic contaminants into onto porous carbonized fractions was dominant at high temperatures (400-700 °C). In addition, surface polarity and aromaticity are important characteristics of biochars, as they affect aqueous organic contaminant sorption (Chen et al., 2008). During adsorption of deisopropylatrazine onto broiler litter-derived biochar, Uchimiya et al. (2010) observed an increase in the sorption capacity with an increase in aromaticity of biochar at 700 °C.

4.3. Biochar as catalyst/support

In recent years, carbon based solid catalysts are gaining much momentum (Mani et al., 2013). Owing to high surface area and high oxygen content mostly in the form of acidic groups such as phenolic and carboxylic, biochar receiving lot of attention and used in cracking of toluene (Mani et al., 2013), catalyzed esterification to produce biodiesel (Dong et al., 2015), electro-oxidation of methanol (Lobos et al., 2016), cracking of phenol (El-Rub et al., 2008), and tars (Shen et al., 2014).

Table 1. Adsorption performance of various biochar materials derived from different feedstocks and pyrolysis temperature.

Feedstock	Pyrolysis temperature (°C)	Heavy metal	Maximum uptake capacity (mg/g)	References
Sida hermaphrodita	700	Cd	35.7	Bogusz et al., 2015
Sida hermaphrodita	700	Cu	33.3	Bogusz et al., 2015
Sida hermaphrodita	700	Zn	48.1	Bogusz et al., 2015
Miscanthus sacchariflorus	600	Cd	13.0	Kim et al., 2013
Pine needles	200	U	62.7	Zhang et al., 2013
Spartina alterniflora	400	Cu	48.5	Li et al., 2013
Corn straw	600	Zn	11.0	Chen et al., 2011
Corn straw	600	Cu	12.5	Chen et al., 2011
Fe-*Gracilaria* biomass	300	As	80.7	Johansson et al., 2016
Fe-*Gracilaria* biomass	300	Se	78.5	Johansson et al., 2016
Fe-*Gracilaria* biomass	300	Mo	38.8	Johansson et al., 2016
Dairy manure	350	Cu	35.3	Xu et al., 2013
Dairy manure	350	Zn	32.4	Xu et al., 2013
Dairy manure	350	Cd	54.6	Xu et al., 2013
Rice husk	350	Pb	29.0	Xu et al., 2013
Rice husk	350	Cu	4.16	Xu et al., 2013
Rice husk	350	Zn	6.60	Xu et al., 2013
Rice husk	350	Cd	7.81	Xu et al., 2013
Rice husk	300	Cu	4.6	Pellera et al., 2012
Olive pomace	300	Cu	5.1	Pellera et al., 2012
Orange waste	300	Cu	4.9	Pellera et al., 2012
Compost	300	Cu	7.9	Pellera et al., 2012

Dehkhoda et al. (2010) generated a biochar-based solid acid catalyst for transesterification of canola oil with alcohol and oleic acid. The catalyst was prepared by treatment with KOH followed by sulfonation of biochar with concentrated sulphuric acid. The authors observed the catalyst yield as 48.1% at high temperature (150 ^{0}C) and pressure (1.52 MPa) for alkali-ester formation with a mixture of canola oil and oleic acid. The authors also pointed out that reusability of the catalyst was also high.

4.4. Biochar in fuel cells

Owing to its unique benefits, fuel cells have been regarded as efficient technique compared to existing power production facilities. Several types of fuel cells have been developed; of these the direct carbon fuel cell (DCFC) is a recently developed technology. DCFC involves converting molten carbonaceous solid fuel directly into electricity without the need of converting the solid into gaseous fuels (Qian et al., 2015). Several investigators utilized biochar as fuel sources (Elleuch et al., 2013; Yu et al., 2014). Ahn et al. (2013) used wood biomass-derived biochar in a direct carbon fuel cell (DCFC) as an alternative fuel. The authors determined that fuel cell power density with biochar as fuel was 60-70% of the coal-based fuel and the performance was further improved by stirring the char bed. Similarly, Elleuch et al. (2013) examined the performance of a DCFC based on ceria-carbonate composite electrolyte fuelled by almond shell-derived biochar. The biochar provided a maximum power output and current density of about of 127 mw/cm^2 and 480 mA/cm^2, respectively, at 750 °C. The authors claimed that that current density delivered by the biochar was double that of delivered by commercial activated carbon.

In recent years, biochars were also used in microbial fuel cell (MFC) electrodes to significantly reduce cost and carbon footprint (Huggins et al., 2014). Even though MFC has lot of advantages such as simultaneous contaminant removal as well as electricity generation, they suffer from drawbacks such as high cost and the non-renewable nature of electrode materials. Huggins et al. (2014) compared the power output cost of activated carbon and graphite electrodes with wood-derived biochar. The authors found that biochar exhibited slightly inferior power output (532-457 mW/m^2) compared to graphite (566 mW/m^2) and activated carbon (674 mW/m^2). However, they further stated that power output cost of biochar (\$17-\$35/W) was 90% lower than that of graphite (\$392/W) and activated carbon (\$402/W). Similarly, Yuan et al. (2013) used sewage sludge-derived biochar as the oxygen reduction reaction catalyst in an MFC. Among the biochar prepared, more positive peak potential and larger peak current of ORR were obtained using the sewage sludge-derived biochar (prepared at 900 °C) compared to those prepared at 500 and 700 °C. In MFCs, the maximum power density of 500 ± 17 mW/m^2 was obtained from the biochar (900 °C) cathode, which was comparable to the Pt cathode.

4.5. Biochar in supercapacitors

Recently, biochar-based supercapacitor materials have attracted research attention. Several results indicated that the use of biochar is promising as an electrode due to its low cost and satisfactory performance (Jin et al., 2013; Gupta et al., 2015). Jiang et al. (2013) indicated that the supercapacitor electrodes, made from red cedar wood-derived biochar exhibited a potential window of about 1.3 V and fast charging-discharging behaviour with a gravimetric capacitance of about 14 F/g. The authors also pointed out that the performance of biochar can be activated with nitric acid and the results indicated that capacitance increased from 14 to 115 F/g after the nitric acid treatment. It should also be pointed out that important step in using biochar for supercapacitors is the activation of the material; however this involves extended hours of high-temperature treatment (around 960 °C) in an inert atmosphere using a strong base (KOH) mixed with biochar powder, followed by chemical washing and prolonged drying (Jin et al., 2013). This energy-intensive and time-consuming process has become a significant barrier in achieving cost-effective biochar supercapacitors. Recently, Gupta et al. (2015) demonstrated a low-temperature (<150 °C) plasma treatment that efficiently activates a yellow pine-derived biochar. The authors observed significant enhancement of the capacitance: 171.4 F/g for a 5-min oxygen plasma activation, in comparison to 99.5 F/g for a conventional chemical activation and 60.4 F/g for untreated biochar.

5. SUMMARY AND FUTURE DIRECTIONS

The review highlights the various preparation methods, potential feedstocks, as well as established and recent applications of biochar. It can be summarized that biochar feedstocks are low-cost and easily available, whereas the technologies for biochar production are largely known. The potential biochar applications include its use as soil amendment to improve soil quality, carbon sequestration and nutrition for plant; as a sorbent for removal of organic and inorganic pollutants from water and soil; as a precursor for catalyst; in supercapacitor; and in fuel cells. It should be noted that several reports pointed out that properties of biochar and its suitability of any further applications depends strongly on the mode of preparation and type of feedstock. However, optimistic claims about biochar can fit into any applications should be avoided. As some authors (Gurwick et al., 2013; Mukherjee and Lal, 2014) stressed that, field studies are very limited, especially while exploring soil benefits of biochar, which are essential for deriving realistic estimates of biochar stability and performance under real-world conditions. In addition, life-cycle and cost-benefit analyses are required to establish threshold biochar application rates under specific scenarios. It should be noted that most of the applications of biochar has only been studied in last few years and additional data especially real field studies will provide comprehensive understanding of biochar technology.

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REFERENCES

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S. and Ok, Y.S. (2014) Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere, 99, 19-33.

Ahn, S.Y., Eom, S.Y., Rhie, Y.H., Sung, Y.M., Moon, C.E., Choi, G.M. and Kim, D.J. (2013) Utilization of wood biomass char in a direct carbon fuel cell (DCFC) system, Applied Energy, 105, 207-216.

Alexandre-Franco, M.F., Gómez-Serrano, V. and Gong, H. (2007) Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. Journal of Colloid and Interface Science, 310, 57-73.

Amutio, M., Lopez, G., Alvarez, J., Moreira, R., Duarte, G., Nunes, J., Olazar, M. and Bilbao, J. (2013) Flash pyrolysis of forestry residues from the Portuguese Central Inland Region within the framework of the BioREFINA-Ter project. Bioresource Technology, 129, 512-518.

Antal, M.J. and Gronli, M. (2003) The art, science, and technology of charcoal production. Industrial and Engineering Chemistry Research, 42, 1619-1640.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A. (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review, Plant and Soil, 337, 1-18.

Bogusz, A., Oleszczuk, P. and Dobrowolski, R. (2015) Application of laboratory prepared and commercially available biochars to adsorption of cadmium, copper and zinc ions from water. Bioresource Technology, 196, 540-549.

Brown, R. (2009) Biochar production technology, Lehmann, J. and Joseph, S. (Eds.), Biochar for Environmental Management: Science and Technology, Earthscan, London.

Cao, X., Ma, L., Gao, B. and Harris, W. (2009) Dairy-manure derived biochar effectively sorbs lead and atrazine. Environmental Science and Technology, 43, 3285-3291.

Chen, B., Zhou, D. and Zhu, L. (2008) Transitional adsorption and partition on nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. Environmental Science and Technology, 42, 5137-5143.

Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M.B. and Hay, A.G. (2011) Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresource Technology, 102, 8877-8884.

Crini, G. (2006) Non-conventional low-cost adsorbents for dye removal: A review. Bioresource Technology, 97, 1061-1085.

Dehkhoda, A.M., West, A.H. and Ellis, N. (2010) Biochar based solid acid catalyst for biodiesel production. Applied Catalysis A General, 382, 197-204.

Devi, P. and Saroha, A.K. (2015) Effect of pyrolysis temperature on polycyclic aromatic hydrocarbons toxicity and sorption behaviour of biochars prepared by pyrolysis of paper mill effluent treatment plant sludge. Bioresource Technology, 192, 312-320.

Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M. and Zhong, Z.-K. (2010) Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water, Air, and Soil Pollution, 213, 47-55.

Dong, T., Gao, D., Miao, C., Yu, X., Degan, C., Garcia-Pérez, M., Rasco, B., Sablani, S.S. and Chen, S. (2015) Two-step microalgal biodiesel production using acidic catalyst generated from pyrolysis-derived bio-char. Energy Conversion and Management, 105, 1389-1396.

Dong, X.L., Ma, L.N.Q. and Li, Y.C. (2011) Characteristics and mechanisms of hexavalent chromium removal by biochar from sugar beet tailing. Journal of Hazardous Materials 190, 909-915.

Duku, M.H., Gu, S. and Hagan, E.B. (2011) Biochar production potential in Ghana—A review. Renewable and Sustainable Energy Reviews, 15, 3539-3551.

El-Rub, Z., Bramer, E.A. and Brem, G. (2008) Experimental comparison of biomass chars with other catalysts for tar reduction. Fuel, 87, 2243-2252.

Elleuch, A., Boussetta, A., Yu, J.S., Halouani, K. and Li Y.D. (2013) Experimental investigation of direct carbon fuel cell fueled by almond shell biochar: Part I. Physicochemical characterization of the biochar fuel and cell performance examination. International Journal of Hydrogen Energy, 38, 16590-16604

Fang, Q., Chen, B., Lin, Y. and Guan, Y. (2013) Aromatic and hydrophobic surfaces of wood-derived biochar enhance perchlorate adsorption via hydrogen bonding to oxygen-containing organic groups. Environmental Science and Technology, 48, 279-288.

Githinji, L. (2014) Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. Archives of Agronomy and Soil Science, 60, 457-470.

Gupta, R.K., Dubey, M., Kharel, P., Gu, Z. and Fan, Q.H. (2015) Biochar activated by oxygen plasma for supercapacitors, Journal of Power Sources, 274, 1300-1305.

Gurwick, N.P., Moore, L.A., Kelly, C. and Elias, P. (2013) A systematic review of biochar research, with a focus on its stability in situ and its promise as a climate mitigation strategy. PLOS One, 8, e75932.

Gwenzi, W., Chaukura, N., Mukome, F.N.D., Machado, S. and Nyamasoka, B. (2015) Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. Journal of Environmental Management, 150, 250-261.

Hu, B., Wang, K., Wu, L., Yu, S.-H., Antonietti, M. and Titirici, M.-M. (2010) Engineering carbon materials from the hydrothermal carbonization process of biomass. Advance Materials, 22, 813-828.

Huggins, T., Wang, H., Kearns, J., Jenkins, P. and Ren, Z.J. (2014) Biochar as a sustainable electrode material for electricity production in microbial fuel cells. Bioresource Technology, 157, 114-119.

Jiang, J., Zhang, L., Wang, X., Holm, N., Rajagopalan, K., Chen, F. and Ma, S. (2013) Highly ordered macroporous woody biochar with ultra-high carbon content as supercapacitor electrodes. Electrochimca Acta, 113 (2013), 481-489.

Jin, H., Wang, X., Gu, Z., Polin, J. (2013) Carbon materials from high ash biochar for supercapacitor and improvement of capacitance with HNO_3 surface oxidation. Journal of Power Sources, 236, 285-292.

Johansson, C.L., Paul, N.A., de Nys, R. and Roberts, D.A. (2016) Simultaneous biosorption of selenium, arsenic and molybdenum with modified algal-based biochars. Journal of Environmental Management, 165, 117-123.

Jung, K.-W., Kim, K., Jeong, T.-U. and Ahn, K.-H. (2016) Influence of pyrolysis temperature on characteristics and phosphate adsorption capability of biochar derived from waste-marine macroalgae (*Undaria pinnatifida* roots). Bioresource Technology, 200, 1024-1028.

Kacprzak, A., Kobyłecki, R., Włodarczyk, R. and Bis, Z. (2014) The effect of fuel type on the performance of a direct carbon fuel cell with molten alkaline electrolyte. Journal of Power Sources, 255, 179-186.

Kameyama, K., Miyamoto, T., Iwata, Y. and Shiono, T. (2016) Influences of feedstock and pyrolysis temperature on the nitrate adsorption of biochar. Soil Science and Plant Nutrition, 62, 180-184.

Kim, W.K., Shim, T., Kim, Y.S., Hyun, S., Ryu, C., Park, Y.K. and Jung, J. (2013) Characterization of cadmium removal from aqueous solution by biochar produced from a giant *Miscanthus* at different pyrolytic temperatures. Bioresource Technology, 138, 266-270.

Laird, D., Fleming, P., Wang, B., Horton, R. and Karlen, D. (2010) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma, 158, 436-442

Lehmann, J. (2007) A handful of carbon. Nature, 447(7141), 143-144.

Lehmann, J. and Joseph, S. (2009) Biochar for environmental management: an introduction. Lehmann, J. and Joseph, S. (Eds.), Biochar for environmental management science and technology, Earthscans, UK, 1-12.

Lehmann, J., da Silva Jr., J.P., Steiner, C., Nehls, T., Zech, W. and Glaser, B. (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil, 249, 343-357.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C. and Crowley, D. (2011) Biochar effects on soil biota - a review. Soil Biology and Biochemistry, 43, 1812-1836.

Leng, L., Yuan, X., Zeng, G., Shao, J., Chen, X., Wu, Z., Wang, H. and Peng, X. (2015) Surface characterization of rice husk bio-char produced by liquefaction and application for cationic dye (Malachite green) adsorption. Fuel, 155, 77-85.

Li, G., Shen, B., Li, F., Tian, L., Singh, S. and Wang, F. (2015) Elemental mercury removal using biochar pyrolyzed from municipal solid waste. Fuel Processing Technology, 133, 43-50.

Li, M., Liu, Q., Guo, L., Zhang, Y., Lou, Z., Wang, Y. and Qian, G. (2013) Cu(II) removal from aqueous solution by *Spartina alterniflora* derived biochar. Bioresource Technology, 141, 83-88.

Lobos, M.L.N., Sieben, J.M., Comignani, V., Duarte, M., Volpe, M.A. and Moyano, E.L. (2016) Biochar from pyrolysis of cellulose: An alternative catalyst support for the electro-oxidation of methanol. International Journal of Hydrogen Energy, In press.

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S. and Qiu, R. (2012) Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar. Water Research, 46, 854-862.

Mani, S., Kastner, J.R. and Juneja, A. (2013) Catalytic decomposition of toluene using a biomass derived catalyst, Fuel Processing Technology, 114, 118-125.

Marris, E. (2006) Putting the carbon back: black is the new green. Nature, 442 (7103), 624-626.

Meng, J., Feng, X., Dai, Z., Liu, X., Wu, J. and Xu, J. (2014) Adsorption characteristics of Cu(II) from aqueous solution onto biochar derived from swine manure. Environmental Science and Pollution Research, 21, 7035-7046.

Mohan, D., Pittman Jr, C.U., Bricka, M., Smith, F., Yancey, B., Mohammad, J., Steele, P.H., Mukherjee, A. and Lal, R. (2014) The biochar dilemma. Sol Research, 52, 217-230.

Mukherjee, A. and Lal, R. (2014) The biochar dilemma. Sol Research, 52, 217-230.

Nartey, O.D. and Zhao, B. (2014) Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: An overview, Advances in Materials Science and Engineering, Article ID 715398, 12 pages.

Oh, T.K., Choi, B., Shinogi, Y. and Chikushi, J. (2012) Effect of pH conditions on actual and apparent fluoride adsorption by biochar in aqueous phase. Water, Air and Soil Pollution, 223, 3729-3738.

Park, S.H., Cho, H.J., Ryu, C. and Park, Y.-K. (2016) Removal of copper(II) in aqueous solution using pyrolytic biochars derived from red macroalga *Porphyra tenera*, Journal of Industrial and Engineering Chemistry, 36, 314-319.

Pellera, F.M., Giannis, A., Kalderis, D., Anastasiadou, K., Stegmann, R., Wang, J.Y. and Gidarakos, E. (2012) Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products. Journal of Environmental Management 96, 35-42.

Qian, K., Kumar, A., Zhang, H., Bellmer, D. and Huhnke, R. (2015) Recent advances in utilization of biochar. Renewable and Sustainable Energy Reviews, 42, 1055-1064.

Renner, R. (2007) Rethinking biochar. Environmental Science and Technology, 41, 5932-5933.

Rondon, M., Ramirez, J.A. and Lehmann, J. (2005) Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration, p. 208.

Rondon, M.A., Lehmann, J., Ramirez, J. and Hurtudo, M. (2007) Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. Biology and Fertility of Soils, 43, 699-708.

Shen, Y., Zhao, P., Shao, Q., Ma, D., Takahashi, F. and Yoshikawa, K. (2014) In-situ catalytic conversion of tar using rice husk char-supported nickel-iron catalysts for biomass pyrolysis/ gasification. Applied Catalysis B Environmental, 152-153, 140-151.

Sohi S.P, Krull E., Lopez-Capel, E. and Bol, R. (2010) A review of biochar and its use and function in soil. Advances in Agronomy, 105, 47-82.

Solaiman, S.M., Murphy, D.V. and Abbott, L.K. (2012) Biochars influence seed germination and early growth of seedlings. Plant and Soil, 353, 273-287.

Takaya, C.A., Fletcher, L.A., Singh, S., Anyikude, K.U. and Ross, A.B. (2016) Phosphate and ammonium sorption capacity of biochar and hydrochar from different wastes, Chemosphere, 145, 518-527.

Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y. and Yang, Z. (2015) Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere, 125, 70-85.

Titirici, M.-M., White, R.J., Falco, C. and Sevilla, M. (2012) Black perspectives for a green future: hydrothermal carbons for environment protection and energy storage. Energy and Environmental Science, 5, 6796-6822.

Uchimiya, M., Klasson, K.T., Wartelle, L.H. and Lima, I.M. (2011) Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations. Chemosphere 82, 1431-1437.

Uchimiya, M., Wartelle, L.H., Lima, I.M. and Klasson, K.T. (2010) Sorption of deisopropylatrazine on broiler litter biochars. Journal of Agricultural and Food Chemistry, 58, 12350-12356.

Uzoma, K.C., Inoue, M., Andry, H., Zahoor, A. and Nishihara, E. (2011) Influence of biochar application on sandy soil hydraulic properties and nutrient retention, Journal of Food, Agriculture and Environment, 9, 1137-1143.

Verheijen, F., Jeffery, S., Bastos, A.C., van Der Velde, M. and Diafas, I. (2009) Biochar application to soil: a critical scientific review of effects on soil properties, processes and functions, EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg.

Vijayaraghavan, K. and Yun, Y.-S. (2008) Bacterial biosorbents and biosorption. Biotechnology Advances 26, 266-291.

Warnock, D.D. Lehmann, J., Kuper, T.W. and Rillig, M.C. (2007) Mycorrhizal responses to biochar in soil—concepts andmechanisms. Plant and Soil, 300, 9-20.

Xu, X., Cao, X. and Zhao, L. (2013) Comparison of rice husk- and dairy manure-derived biochars for simultaneously removing heavy metals from aqueous solutions: Role of mineral components in biochars. Chemosphere, 92, 955-961.

Yu, F., Li, Y., Han, S. and Ma, J. (2016) Adsorptive removal of antibiotics from aqueous solution using carbon materials. Chemosphere, 153, 365-385.

Yu, J., Zhao, Y. and Li, Y. (2014) Utilization of corn cob biochar in a direct carbon fuel cell. Journal of Power Sources, 270, 312-317.

Yuan, J.-H. and Xu, R.-K. (2011) The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. Soil Use and Management, 27, 110-115.

Yuan, Y., Yuan, T., Wang, D., Tang, J. and Zhou, S. (2013) Sewage sludge biochar as an efficient catalyst for oxygen reduction reaction in an microbial fuel cell. Bioresource Technology, 144, 115-120.

Zhang, M., Gao, B., Yao, Y., Xue, Y. and Inyang, M. (2012) Synthesis of porous MgO biochar nanocomposites for removal of phosphate and nitrate from aqueous solutions. Chemical Engineering Journal, 210, 26-32.

Zhang, Z.B., Cao, X.H., Liang, P. and Liu, Y.H. (2013) Adsorption of uranium from aqueous solution using biochar produced by hydrothermal carbonization. Journal of Radioanalytical and Nuclear Chemistry, 295, 1201-1208.

Zhao, L., Cao, X., Mašek, O. and Zimmerman, A. (2013) Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. Journal of Hazardous Materials, 256-257, 1-9.

Zheng, W., Guo, M., Chow, T., Bennett, D.N. and Rajagopalan, N. (2010) Sorption properties of greenwaste biochar for two triazine pesticides. Journal of Hazardous Materials, 181, 121-126.