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SMART biochar technology—A shifting paradigm towards advanced materials and healthcare research

Yong Sik Ok [a,1], Scott X. Chang [b,*], Bin Gao [c,2], Hyun-Joong Chung [d,3]

[a] *Korea Biochar Research Center and Department of Biological Environment, Kangwon National University, Chuncheon 200-701, Republic of Korea*

[b] *Department of Renewable Resources, University of Alberta, Edmonton, Canada*

[c] *Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, 32611, USA*

[d] *Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Canada*

HIGHLIGHTS

- Biochar applications range from soil fertility improvement to removal of contaminants.
- New approaches such as engineered and designer biochars are being rapidly developed.
- Biochars developing into advanced materials and healthcare research and applications.
- Biochar technology poised for commercialization in multiple fields.

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ABSTRACT

Biochar, produced through pyrolysis of biomass under low or no oxygen conditions, has found a wide range of applications from soil fertility improvement to removal of contaminants. Initial interest in biochar is to use it as a means to capture carbon dioxide from the atmosphere; however, recent developments are seeing biochar being applied in engineering, and health care and life sciences, some of those applications have large potentials for rapid commercialization. We expect a paradigm shift towards the development of the next generation of biochar with applications in a range of new fields.

Contents

Since the recent breakthrough in biochar research (Lehmann, 2007), numerous studies have been conducted on the use of biochar for agronomic and environmental benefits (cf., Zhang and Ok, 2014). Biochar, a solid carbon material produced

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[*] Corresponding author. Tel.: +1 780 492 6375; fax: +1 780 492 6375.
E-mail addresses: soilok@kangwon.ac.kr (Y.S. Ok), scott.chang@ualberta.ca (S.X. Chang), bg55@ufl.edu (B. Gao), chung3@ualberta.ca (H.-J. Chung).

[1] Tel.: +82 33 250 6440.

[2] Tel.: +1 352 392 1864x285.

[3] Tel.: +1 780 492 4790.

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through pyrolysis of biomass without oxygen or under low oxygen availability, has been applied in various regions of the world to improve soil fertility and sequester carbon (C) via exploitation of its nutrients, its high C content and the refractory nature of the C contained (Chan et al., 2007; Sohi, 2012; Novak et al., 2015).

The initial interest in biochar is to use it as a means to capture carbon dioxide from the atmosphere and store the carbon in the soil in a very stable form (Sohi, 2012). In this regard, biochar production has been described as a carbon-negative technology that can provide effective mitigation for climate change (Gaunt and Lehmann, 2008; Glaser et al., 2009). While biochar's effect on soil CO_2 fluxes are more variable, with most publications reporting minor or no effects, its influence on reducing N_2O emissions is noteworthy (Spokas and Reicosky, 2009; Wu et al., 2013; Thomazini et al., 2015), as N_2O is a much more potent greenhouse gas than CO_2.

The concept of designer biochar extended the potential application of biochar as an alternative fertilizer to improve soil quality; in the designer biochar concept, the production of biochar is tailored by selecting different feedstocks and using different pyrolysis conditions to form specific chemical and physical characteristics matched to improve specific properties of degraded soils (Novak et al., 2009, 2014). In addition, recent studies showed that biochar can be used as an adsorbent to control and remediate various contaminants in soil and water systems (Ahmad et al., 2014; Mohan et al., 2014). The designer biochar concept can be equally applied to the environmental science area to improve the efficiency of contaminant removal, for example, by matching biochar properties with the behavior of contaminants.

A recent review summarized advances in the utilization of biochar as catalysts, soil amendments, contaminant absorbents, components of fuel cell systems, media for gas storage and precursors for producing activated carbon (Qian et al., 2015). Rapid expansion has been made in the application of biochar into areas not previously considered, showing a tremendous potential of biochar in a wide array of areas. For example, as reviewed in Qian et al. (2015), biochar is being used as a catalyst for syngas cleaning and for conversion of syngas into liquid hydrocarbons, and as a solid acid catalyst for biodiesel production. Life cycle assessment provides additional support for the adoption of the biochar technology in agricultural, energy and environmental sectors (Woolf et al., 2010; Novak et al., 2015). Some of the claims on biochar benefits are based on one or some aspects of the function of biochar without considering other effects of biochar and as such misleading conclusions are sometimes reached; therefore performing the full analysis of the biochar effects or functions in a form of life cycle analysis is critical (Field et al., 2013; Frazier et al., 2015).

Recently the concept of engineered biochar has been developed and a novel engineered biochar, a biochar-based nanocomposite with improved physicochemical and sorptive properties, has been used for various environmental applications including contaminant removal and reclamation of sites containing excessive nutrients (Zhang et al., 2012; Yao et al., 2013). The key aspect of the engineered biochar concept is similar to that of designer biochar where biochar is produced with specific and controlled properties for particular purposes, be it for carbon sequestration, soil fertility improvement, or waste management and pollution control (Shackley et al., 2013). The environmental application system for biochar is now not only a well-established area for basic scientific research, but also an emerging industrial field with a rapid pace of commercialization (IBI, 2014). As of today, more than 50 regional biochar groups have been organized, with field trials being conducted in various regions of the world (IBI, 2014). Studies on the physical, chemical, and biological properties of biochar will inevitably open up interdisciplinary research areas for the application of biochar in material and life sciences.

Biochar as a product of pyrolysis of biomass can be produced inexpensively. When compared with activated carbon, a highly porous material with a superior surface area and adsorptive capacities, biochar is typically processed at lower temperatures in a shorter time period, thus it typically contains volatile material fractions such as tars, oils, and other pyrolytic compounds (Azargohar and Dalai, 2006). An upgrade from biochar to activated carbon can be instrumental in high-end applications, such as in energy and healthcare fields, but the process has been considered not energy-efficient because it requires very high temperatures (>900 °C) to produce high-quality activated carbon materials. A recent research suggests a novel strategy to use oxygen plasma to upgrade biochar at a temperature lower than 150 °C(Gupta et al., 2015), demonstrating a strong potential to expand the horizon of biochar application to various smart materials.

Recent reports utilized biochar as a supercapacitor, an energy storage device (Jiang et al., 2013; Wang et al., 2013; Gupta et al., 2015). Coupled with its readily available nature and low cost and low environmental impact, carbon materials with high surface areas and a porous structure are desirable raw material for making supercapacitors (Liu et al., 2012). Biochar has been reported to have the potential to meet the cost and performance targets required for manufacturing supercapacitors and biochar supercapacitors have the potential for broad applications (Jiang et al., 2013; Wang et al., 2013; Gupta et al., 2015). In addition, engineered biochars (coated with graphene) have been found to have an excellent reversible discharge capacity and are thus suitable for use as an anode material for making batteries (Zhang et al., 2013). We expect a paradigm shift towards the development of the next generation of biochar with applications in fields including but not limited to the following: for the manufacturing of supercapacitors, batteries, sensors, smart building materials, animal feed, healthcare products and microbial fuel cells, and for application in building green cities and in drug delivery (Suguihiro et al., 2013; Wang et al., 2013).

The long history of charcoal use in medicine with its strong absorbability of toxins (Bond, 2002) supports the concept of applying biochar in healthcare systems, with biochar as the precursor of activated charcoal as one potential area of application (Azargohar and Dalai, 2006; Qian et al., 2015). Recent application of activated charcoal composites as a biomaterial in promoting human embryonic stem cell differentiation (Chen et al., 2012) strongly indicates the efficacy of biochar in biomedical applications. Activated carbon is routinely used for detoxification or decontamination of poisoning or drug overdose (Wall et al., 2009; Azkunaga et al., 2011; Roca et al., 2014). Activated carbon has also been shown to be effective in the protection against cytotoxicity and genotoxicity from deoxynivalenol, a typical grain contaminant that occurs from field conditions or during storage (Abdel-Wahhab et al., 2015). The concept of a SMART biochar system can be applied in health care research for uses such as filler media and drug-delivery agents (Bielicka et al., 2013; de Gunzburg et al., 2015). In addition, biochar can serve as a sensor material. For example, a biochar-based voltammetric sensor has recently been reported to detect toxic heavy metal ions such as Pb^{2+} and Cd^{2+} (Suguihiro et al., 2013). Many of such applications in healthcare systems will likely be indirect, for example, through the removal of toxins from the soil, water and other environmental media to reduce the risk of negative impacts toxins on human health (Beesley et al., 2010; Khan et al., 2014; Zheng et al., 2015).

Understudied fields related to biochar include the establishment of protocols, production standards, and standardized characterization methods for new biochar-based materials. Toxicity assessment is required prior to the use of biochar in humans and in the management of ecosystems when biochar is applied in healthcare systems or to the environment (Busch et al., 2013; Anjum et al., 2014). Even though great advances have been made to understand biochar properties and to design biochar for specific purposes (Novak et al., 2009, 2015), the relationship between the chemical and physical properties of biochar and biochars' applicability in different fields is still poorly understood and it is still difficult to establish process conditions to produce biochars with desired characteristics (Manya, 2012). Expanded research efforts will provide solutions to those problems in the near future. To help advance the application of biochar for specific purposes, it is critical that details about the properties of the biochar, the feedstock type and conditions used for making the biochar are reported to establish the appropriate process conditions for producing biochars with more desirable characteristics (Manya, 2012).

Above all, biochar is a readily obtainable and renewable form of carbon material and its chemical properties can be easily altered to achieve functions required for various applications through altering the condition for pyrolysis and the type of feedstock used (Keiluweit et al., 2010); that is the promise for making designer or engineered biochars and for advancing the paradigm shift towards advanced materials and healthcare research. The concept of designer/engineered biochar can be further extended to functional materials. Biochar as a historically explored, yet inadequately exploited, class of material that can be derived from naturally abundant feedstocks has the potential to open up a vast range of opportunities in the production of functional materials. We believe that the rapidly growing and strong interest in biochar will bring biochar research and application into a new era. Biochar is a treasure from an old chest; the historic and renewable material is currently being reinvigorated to revolutionize its application in global environmental and human health management.

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