Biochar: Industrial Applications

A White Paper

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Advanced biofuels show great promise to reduce dependence on foreign oil as well as decrease CO_2 emissions from traditional petroleum fuel sources. Increasing renewable fuel standard mandates demonstrate the need for new non-traditional biofuel sources and give way for new market opportunities in bio-energy industries. One method of producing these advanced biofuels is the thermal transformation of solid biomass through the process of pyrolysis. During pyrolysis, the feedstock is heated in a closed chamber to high temperatures (>500° C) in the absence of oxygen (O_2). This process generates syngas (CH_4, H_2 CO_2, and CO), biochar and an aqueous fraction containing pyroligneous acid (wood vinegar) and liquid smoke. Whereas syngas can be condensed and refined into drop-in fuels like biodiesel, biochar can take on a variety of different industrial uses typically fulfilled by higher cost products.

Pyrolysis is an established technology. The historic production of charcoal for use in agriculture has been dated to pre-Columbian societies and their utilization of char to develop ‘terra preta’ or ‘black earth’ soils (Neves, Petersen, Bartone, & Heckenberger, 2004). Much of modern research on biochar application has continued to be focused on its use as a soil amendment to improve agricultural productivity. New research suggests that the potential applications for char may extend beyond traditional applications and into a variety of other industrial processes including toxicological remediation, wastewater treatment, livestock production, and climate change mitigation.

Properties

The physical properties of biochar determine many of its practical applications. During pyrolysis, thermal decomposition will leave behind a microporous carbon skeleton resembling the original structure. This gives the biochar an extremely high surface area (500–2000 m^2 g^{-1}), a relatively low density, and excellent adsorptive properties (Lehmann & Joseph, 2009). These properties are greatly influenced by the properties of the biomass feedstock including the cellulose, hemicellulose, and lignin content, inorganic composition, and pre-handling conditions. Additionally, the conditions of pyrolysis such as temperature, reaction time, and reactor type contribute to the properties of the final product. It is possible to increase the surface area and porosity of biochar through industrial activation processes including chemical and physical activation.

Microporosity and Macroporosity

Just as with traditional activated carbon, the micropores (<2nm diameter) and macropores (>50nm diameter) found in biochar are responsible for many of its industrial applications. Micropores generally facilitate the adsorption of small molecules which is useful in a variety of filtration applications including both gaseous and aqueous filtration (Lehmann & Joseph, 2009). Macropores, on the other hand, are responsible for other properties including soil aeration and water absorptivity, microbial habitat facilitation, large particle binding, and bulk volume.

Surface Area

The high surface area of most biochars is attributed to its porosity. The value of surface area is apparent in many of the same applications as porosity including molecule adsorption, microbial growth, high cation exchange capacity (CEC), and water absorption.

Feedstock

Pyrolysis, and by extension biochar, it extremely flexible in regards to potential feedstocks. Most organic wastes can be pyrolized, though the process lends itself best to feedstocks that are high in cellulose and low in moisture. This suggests that pyrolysis holds promise as a potential value added pathway for many waste products including agricultural residue, forestry slash, and even anaerobic digestate. The initial properties of the feedstock greatly affect the properties of the final product. While any biomaterial with sufficiently low moister content can be pyrolized, certain feedstocks produce higher quality products on a more consistent basis. High carbon feedstocks will generally produce high carbon biochar, and the morphological characteristics are highly dependent on original feedstock conditions including particle shape, size, and surface area. In general, high lignin, high surface area feedstocks result in the most constant product. To determine optimal applications, biochar is best characterized on an individual batch basis.

Applications

Soil Amendment

One of the most commonly studied applications of biochar is its use as an agricultural soil amendment. Because of its porous structure, biochar creates a habitat for beneficial microorganisms, increasing total stored macronutrient content, cation-exchange capacity (CEC), water absorption capacity, and organic matter content. In most cases, it will also increase total pH of the soil, making it a great replacement for the traditional practice of using lime to raise soil pH. When accounted for each of these properties synergistically, biochar becomes an economically effective agricultural product.

Improvements in harvest yield may be one of the most appealing agricultural properties of biochar. Many studies have found biochar amendments to cause significant increases to yields. Asai et. al. (2009) found biochar (teak and rosewood residues) amendment at a rate of 8 t ha^{-1} in low nutrient rice fields increased grain yield by 25% from control with no added nutrients and by as much as 100% from positive control with added nitrogen and phosphorus. Other studies including those summarized by Galinatio, Yoder, and Granatstein (2011) (softwood bark)show a similar trend with winter wheat of yield increase, with a much higher increase when used with additional fertilization.

It should be noted that short term yields in biochar amended crops may decrease as raw biochar will temporarily adsorb bioavailable nutrients if at high application rates. Long term yields have been shown to increase after the first growing season.

Field Nutrient Loss Mitigation

Total soil organic matter is a key metric in determining a soils ability to hold nutrients (Paustian, Parton, & Persson, 1992). In sandy-loam soils, as much as 50% of fertilizers can be lost through runoff, erosion, or infiltration soon after application (Johnston, et al., 1994). A smaller proportion will also volatilize and be lost as atmospheric nitrogen in the form of N_2 or N_2O, a potent greenhouse gas (GHG). Biochar is effective at preventing nitrogen loss from runoff and infiltration and reduces the amount lost through volatilization. A 2% dry w/w biochar (pine, oak, mixed, bamboo, leaves) composition can reduce the total N_2O/N_2 emission ratio by up to 90% of non-amended fertilized soils (Cayuela, et al., 2013). This principle also applies to point-source nutrient spikes. When biochar (green waste, poultry manure) is amended to soils at a rate of 30 t ha^{-1}, N_2O emissions from cattle urine was reduced by more than 50% (Taghizadeh-Toosi & Clough, 2011). These effects are likely due to the ability of biochar to facilitate the last step of denitrification from N_2O to N_2.

Livestock Growth

Biochar can have various beneficial effects on livestock production when ingested as a feed supplement or used in feed processing. When added as a supplement to recommended feed at a rate of 0.2%, biochar (corn cob, canarium seed) can increase total weight and improve total body characteristics of broiler chicken (Kana & Teguia, 2010). This has been repeated in studies with cattle showing a ration with 0.5% biochar (rice husk) can increase body weight by up to 25% while at the same time reducing methane emissions by up to 22% (Leng & Preston, 2012).

Compost Processing

Biochar has a number of beneficial effects when applied to the organics composting process including odor reduction and GHG emission reductions. Industrial composting facilities often have odor control problems stemming from the natural production of NH_3 and H_2S. Biochar has been shown to be more effective at mitigating these types of odors more efficiently than the current alternative of activated carbon (Ma, Wilson, Zhao, Yorgey, & Frear, 2013).

Biochar has also been found to decrease nitrogen loss from N_2O emissions. Studies examining poultry liter, pig manure, and sewage sludge composting processes amended with 9 to 20% biochar (bamboo, poultry litter) have demonstrated total reductions in N_2O emissions ranging from 52 to 65% from that of the control (Hua, Wu, Liu, McBride, & Chen, 2009; Chen, et al., 2010; Steiner, Das, Melear, & Lakly, 2010). This is due to its support of denitrifying bacteria, much like the effects seen in agricultural applications.

Because of biochar's microporous structure, previously anaerobic conditions within compost may become aerobic. This reduces the ratio of methanogenic to methanotrophic bacteria, decreasing the total CH_4 emissions by converting it to CO_2 (Sonoki & Furukawa, 2012).

Wastewater Toxicant Removal

Because of its high affinity to adsorb molecular ions, biochar has demonstrated excellent potential in a variety of toxicological mediation strategies. It has been shown effective in mitigating aqueous metals, suspended solids, organic compounds, and organic hydrocarbons in a variety of industrial applications including urban and residential storm water runoff, resource extraction runoff, industrial yard runoff, and industrial wastewater filtration. Furthermore, raw biochar (sugar cane) has been found to be as effective as traditional activated carbon in toxicant immobilization (Carrier, Hardie, Uras, Görgens, & Knoetze, 2012). This principle can be applied to either a water filtration strategy or a solid immobilization strategy by amending biochar to contaminated media to prevent contaminant runoff and infiltration.

Urban storm water runoff contains a variety of contaminants including dissolved metals, polycyclic aromatic hydrocarbons (PAHs), and suspended solids, each of which often exceed local and federal regulations. Biochar offers promise as a low-cost alternative to current strategies like filtration and bioretention. The Port of Tacoma, WA has recently successfully tested a 30% biochar (hardwood) to 70% sand ratio as a filtration media to remove point-source and non-point-source Zn, Cu, and suspended solids from log yard storm water effluent (Kennedy Jenks Consultants, 2014). Various other lab scale experiments have demonstrated similar successes. Column filtration tests with biochar (green waste, poultry litter, waste wood, digerster waste) show toxic metal (Cd, Cr, Cu, Pb, Ni, and Zn) reduction ranging from 17 – 75% depending on the metal, total suspended solid reduction of around 86%, nitrate reduction of 86%, and up to 100% efficiency at removing some PAHs (Park & Choppala, 2011; Inyang & Gao, 2012; Reddy, Xie, & Dastgheibi, 2014). It has been shown that different types of biochar are highly selective for the metals they adsorb due to differences in pore size and other properties (Caporale & Pigna, 2014). Other uses of biochar in urban storm water filtration scenarios include incorporation into rain gardens and sensitive buffer strips to bolster bioretention attributes.

Contaminant immobilization near industrial applications is also seen to be highly effective. Biochar used as a medium in hydrologically sensitive areas including streams, lakes, and aquifers buffers can reduce the contamination potential from agricultural and industrial applications. When amended to historical mining drainage sites, biochar (poultry litter) has been effective at immobilizing toxic metals including Cu, Zn, As, and Pb within contaminated soils (Seok-Young & Myong-Keun, 2013; Min-Suk & Hyun-Gi, 2014). Various types of biochar also show promise as a filtration method for fracking wastewater. Some biochars (oak, pine) have been able to remove up to 95% of residual hydrocarbons and up to 46% of various organic salts commonly used in fracking operations (Cooks, 2014). These specific applications can be expanded upon to encompass many other sensitive contaminant scenarios where toxicant removal is pertinent for regulatory compliance.

Carbon Sequestration and Credits

Net primary producers (trees, crop, etc.) sequester CO_2 as organic matter while they grow. Once the organic matter becomes detritus, much of the carbon will shortly convert the organic matter back to CO_2 through decomposition. If the organic matter is converted to biochar before decomposition, much of the stored carbon will be sequestered for upwards of thousands of years (Lehmann & Joseph, 2009). This gives way as a possible outlet for biochar to generate carbon credits upon accreditation by carbon market administrations.

The viability and magnitude of net negative GHG emissions is directly dependent on the type of feedstock and management practices involved which would affect GHG emissions including transportation, processing, and energy use. Intensive practices may not be suitable for this method due to the stringent nature of carbon credit regulation. Roberts et. al. (2010) showed that the net emission reductions from corn stover and yard waste amounted to 864 and 885 kg CO_2e ton^{-1} feedstock when amended to soil. Gaunt et. al. (2007) showed that upwards of 60% of original carbon will be permanently stored.

Availability and Demand

As one of the byproducts of advanced biofuel creation, the availability of biochar is expected to increase in the coming years. While it has not yet been heavily industrialized, the abundance of pyrolytic processors is increasing rapidly in conjunction with the demand of advanced biofuels. Consequently, there will be a surplus of biochar suitable for all of the applications outlined above. Biochar has demonstrated excellent potential for replacing traditional products like activated carbon, as well as branching into new fields ranging from organics composting to industrial agricultural production.

Works Cited

Asai, H., Samson, B., Stephan, H., Songyikhangsuthor, K., Homma, K., Kiyono, Y., . . . Horie, T. (2009). Biochar amendment techniques for upland rice produciton in Northern Laos; Soil physical properties, leaf SPAD and grain yield. Field Crops Research, 111, 81-84. doi:10.1016/j.fcr.2008.10.008

Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2010). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. Soil Research, 48(7), 531-545. doi:10.1071/SR10014

Caporale, A. G., & Pigna, M. (2014). Effect of pruning-derrived biochar on heavy metals removal and water dynamics. Biology and Fertility of Soils. doi:10.1007/s00374-014-0960-5

Carrier, M., Hardie, A., Uras, Ü., Görgens, J., & Knoetze, J. (2012). Production of char from vacuum pyrolysis of South-African sugar cane bagasse and its characterization as activated carbon and biochar. Journal of Analytical and Applied Pyrolysis. doi:10.1016/j.jaap.2012.02.016

Cayuela, M. L., Monedero-Sanchez, M. A., Roig, A., Hanley, K., Enders, A., & Lehmann, J. (2013). Biochar and denitrification in soils: when, how much and why does biochar reduce N_2O emissions. Scientific Reports, 1732(3). doi:10.1038/srep01732

Chen, Y., Huang, X., Han, Z., Huang, X., Hu, B., Shi, D., & Wu, W. (2010). Effects of bamboo charcoal and bamboo vinegar on nitrogen conservation and heavy metals immobility during pig manure composting. Chemosphere, 78(9), 1177-1181. doi:10.1016/j.chemosphere.2009.12.029

Cooks, S. T. (2014). Adsorption of contaminants found in hydraulic fracking produced water utilizing cost-effective biochar treatment. The University of Texas at San Antonio. Retrieved from http://gradworks.umi.com/15/56/1556483.html

Galinatio, S., Yoder, J., & Granatstein, D. (2011). The economic value of biochar in crop production and carbon sequestration. Energy Policy, 39, 6344-6350. doi:10.1016/j.enpol.2011.07.035

Gaunt, J., & Lehmann, J. (2007). Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis BIoenergy Production. Environmental Science and Technology. doi: 10.1021/es071361i

Hao, X., Chang, C., & Larney, F. (2004). Carbon, Nitrogen Balances and Greenhouse Gas Emissions during Cattle Feedlot Manure Composting. Journal of Environmental Quality. doi:10.2134/jeq2004.3700

Hua, L., Wu, W., Liu, Y., McBride, M., & Chen, Y. (2009). Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. Environmental Science and Pollution Research, 16(1), 1-9. doi:10.1007/s11356-008-0041-0

Inyang, M., & Gao, B. (2012). Removal of heavy metals from aqueous solutions by biochars derived from anaerobically digested biomass. Bioresource Technology. doi:10.1016/j.biortech.2012.01.072

Johnston, A., McEwen, J., Lane, P., Hewitt, M., Poulton, P., & Yeoman, D. (1994). Effects of one to six year old ryegrass-clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans (Vicia faba) grown on a sandy loam soil. The Journal of Agricultural Science, 122(01), 73-89. doi:10.1017/S0021859600065825

Kana, J. R., & Teguia, A. (2010). Growth performance and carcass characteristics of broiler chickens fed diets supplimented with graded levels of charcoal from maize cob or seed of Canarium schweinfurthii Engl. Tropical Animal Health and Productivity. doi:10.1007/s11250-010-9653-8

Kennedy Jenks Consultants. (2014). Bench and Pilot Scale Testing of Novel Treatment Media. Portland, OR. Retrieved from http://www.kennedyjenks.com/wp-content/uploads/StormCon_2014_BenchScale-PilotTesting.pdf

Lehmann, J., & Joseph, S. (2009). Biochar for Environmental Management: Science and Technology. London: Earthscan.

Leng, R. A., & Preston, T. R. (2012). Biochar reduces enteric methane and improves growth and feed conversion in local “Yellow” cattle fed cassava root chips and fresh cassava foliage. Livestock Research for Rural Development. Retrieved from http://www.lrrd.cipav.org.co/lrrd24/11/leng24199.htm

Ma, J., Wilson, K., Zhao, Q., Yorgey, G., & Frear, C. (2013). Odor in Commercial Scale Compost: Literature Review and Critical Analysis. Olympia: Washington State Department of Ecology.

Major, J., Rondon, M., Molina, D., Riha, S., & Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil, 333, 117-128. doi:10.1007/s11104-010-0327-0

Min-Suk, K., & Hyun-Gi, M. (2014). The effectiveness of spend coffee grounds and its biochar on the amelioration of heavy metals-contaminated water and soil using chemical and biological assessments. Journal of Environmental Management. doi:10.1016/j.jenvman.2014.07.001

Neves, E., Petersen, J., Bartone, R., & Heckenberger, M. (2004). The Timing of Terra Preta Formation in the Central Amazon: Archaeological Data from Three Sites. In Amazonian Dark Earths: Explorations in Space and Time (pp. 125-134). Springer Berlin Heidelberg. doi:10.1007/978-3-662-05683-7_9

Park, J. H., & Choppala, G. (2011). Biochar reduces the bioavailability and phytotoxicity of heavy metals. Plant Soil. doi:10.1007/s11104-011-0948-y

Paustian, K., Parton, W., & Persson, J. (1992). Modeling Soil Organic Matter in Organic-Ammended and Nitrogen-Fertilized Long-Term Plots. Soil Science Society of America. doi:10.2136/sssaj1992.03615995005600020023x

Reddy, K. R., Xie, T., & Dastgheibi, S. (2014). Evaluation of Biochar as a Potential Filter Media for the Removal of Mixed Contaminants from Urban Strom Water Runoff. Journal of Environmental Engineering. doi:10.1061/(ASCE)EE.1943-7870.0000872

Roberts, K., Gloy, B., Joseph, S., Scott, N., & Lehman, J. (2010). Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. Environmental Science Technology, 44, 827-833. doi:10.1021/es902266r

Seok-Young, O., & Myong-Keun, Y. (2013). Biochar for Treating Acid Mine Drainage. Environmental Engineering Science. doi:10.1089/ees.2013.0063

Sonoki, T., & Furukawa, T. (2012). Influence of biochar addition on methane metabolism during thermophilic phase of composting. Journal of Basic Microbology. doi:10.1002/jobm.201200096

Steiner, C., Das, K., Melear, N., & Lakly, D. (2010). Reducing nitrogen loss during poultry litter composting using biochar. Journal of Environmental Quality, 39(4), 1236-42.

Taghizadeh-Toosi, A., & Clough, T. (2011). Biochar Incorporation into Pasture Soil Suppresses in situ Nitrous Oxide Emissions from Ruminant Urine Patches. Journal of Environmental Quality. doi:10.2134/jeq2010.0419