LIFE CYCLE ASSESSMENT OF ACTIVATED CARBON FROM WOODY BIOMASS[1]

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Abstract. Activated carbon (AC) developed and marketed for water and gas purification is traditionally made from hard coals (fossil-based materials). However, increasing awareness of environmental impacts caused by fossil fuel consumption and fossil-based products has provided a market opportunity for renewable and low-impact biobased products as alternatives including AC. The huge volumes of woody biomass generated from forest management activities could be used as feedstocks for these new bioproducts. These new bioproducts require evaluation to determine if they are low impact. To aid in quantifying environmental impacts of a new bioproduct (such as AC), this study developed the cradle-to-gate life cycle inventory (LCI) data for the carbon activation of biochar in a rotary calciner by collecting operational and direct emission data while conforming to the internationally accepted life cycle assessment method. The LCI data were then modeled to develop the life cycle impact assessment profile of biochar-based carbon activation and compared with commercial coal-based carbon activation. The results showed about 35% less cradle-to-product gate cumulative energy demand for the biochar AC system compared with the coal AC system. Consequentially, the greenhouse gas emissions for biochar AC production were less than half that of coal AC production (8.60 kg CO_2 eq vs 18.28 kg CO_2 eq per kg of AC produced). This was because of both lower energy consumption and the biogenic carbon benefit from using woody biomass for both feedstock and processing. To ensure substitution of the two ACs, the physical properties for the AC from biochar and coal were compared for their Brunauer–Emmett–Teller surface area and iodine number, which showed that both indicators were superior for biochar AC compared with coal AC. Therefore, biochar AC results from this study suggest a potential high-value market for woody biomass derived from forest restoration and wildfire suppression activities.

Keywords: Activated carbon, biochar, coal, LCA, comparative assertion, GHG mitigation.

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INTRODUCTION

In light of increased awareness of the environmental problems associated with fossil fuels, substitution of fossil fuels with renewable bioenergy and bioproducts is being considered (Tilman et al 2009; Lippke et al 2012) and is on the rise. The sustainable aspect of bioenergy from biomass provides security in increasing worldwide energy demand and price volatility (CBO 2012; USEIA 2018a, 2018b). Biomass pyrolysis is one such bioconversion process that has received considerable attention in recent years that also produces bioproducts along with bioenergy (Garcia-Nunez et al 2017; Roy and Dias 2017; Kataki et al 2018). Pyrolysis is a thermal decomposition of biomass occurring in an inert environment, generating biochar, synthesis gas (syngas), and bio-oil depending on operating conditions. In addition to interest in producing bioenergy from such technology, bioproducts such as biochar with high carbon storage are receiving more and more interest for their greenhouse gas (GHG) mitigation potential (Bergman at al 2016; Buchholz et al 2016).

Bioenergy and bioproducts have close connections to feedstock production, especially in the agricultural and forestry sectors. For example, in the United States, there has been great demand for increased management of western forests to decrease threats from wild forest fires, insect and disease outbreaks, and invasive species (Wienk et al 2004; Hutto 2008). Managing these threats will require restoration treatments, such as thinning dense stands and harvesting dead timber (Anderson and Mitchell 2016; Hensen et al 2016). Such activities produce large amounts of woody biomass, which can be used as feedstock for production of bioenergy and bioproducts (Stokes et al 2016).

Both the US Department of Energy and the US Department of Agriculture are strongly committed to expanding the role of biomass as a clean and renewable energy source and to understand the carbon implications in biomass-to-bioproducts conversion. For example, these two agencies jointly formed the Biomass Research and Development Initiative (BRDI) to support the development of a biomass-based industry in the United States for energy production and environmental protection. One outcome of this initiative is a project showing vast woody feedstock availability potential; about 93.1 million dry tons of forest residues and woody biomass are estimated to be available in 2022 (USDOE 2016). The life cycle assessment (LCA) presented here was funded by BRDI as a component of an integrated evaluation of biomass feedstock production, logistics, conversion, distribution, and end use focused on an innovative thermochemical conversion system using woody biomass feedstocks (Miller et al 2014, 2015).

Biochar is the solid material generated by the pyrolysis of biomass and is normally considered a coproduct of bioenergy production. It can be used as a soil amendment or alternatively made into activated carbon (AC) for air and water purification treatment (Pollard et al 1992; Munoz et al 2007; del-Campo et al 2015). AC is a higher value-added product than biochar, and there are potential additional environmental benefits associated with the biochar to AC conversion (Bayer et al 2005; Hjaila et al 2013). Commercial AC products are primarily made from hard coals because they are cheap, readily available, and have high carbon content (Zou and Han 2001). AC is a crude form of graphite. The graphite structure gives the carbon very large surface area, which allows the carbon to absorb a wide range of compounds in liquid or gaseous form. Because of its strong adsorption forces, or volume of adsorbing porosity, AC is widely used for filtration of drinking water or for removal of contaminates and micropollutants from waste water streams. AC can be produced from a variety of carbon-containing feedstocks such as wood and coconut shells, in addition to anthracite and bituminous coals (Marsh and Reinoso 2006). There are very few AC products made from woody biomass available on the market, and none have been evaluated for environmental performance.

LCA is a well-established and internationally accepted method for categorizing GHG emissions and other impacts from industrial processes (ISO 2006a, 2006b). LCA has been widely used in

recent years to evaluate the environmental impacts of converting biomass to bioenergy products, including liquid fuel for transportation or electricity (Cherubini and Stromman 2011; Sebastian et al 2011; Steubing et al 2011; Field et al 2013; Hertwich et al 2013; Pierobon et al 2014; Stephenson and MacKay 2014; Gu and Bergman 2016). As noted previously, LCA literature has focused on the carbon activation process from alternative feedstocks, such as wood. It is also very limited and is usually accompanied by incomplete LCA datasets. In conjunction with limited data, previous LCA research on coal AC has been imbedded in water and waste gas purification and waste water treatment studies (Meier 1997; Bayer et al 2005) and not the activation process itself. For bio-based AC products, literature includes studies on wood (del-Campo et al 2015), olive-waste cake (Hjaila et al 2013), coconut shells (Iqbaldin et al 2013; Arena et al 2016), oat hulls and corn stover (Fan et al 2004), and sugar cane bagasse (Ruiz and Rolz 1971). Hjaila et al (2013) did a gate-to-gate LCA on AC made from an olive by-product, ie olive-waste cakes with a laboratory-scale chemical activation process. The cumulative energy demand (CED) for the gate-to-gate production was 168 MJ/kg AC. They found the global warming (GW) impact of their olive-waste AC product was 11.1 kg CO_2/kg AC, very close to Bayer et al (2005) virgin coal granular–AC product, which was 11.0 kg CO_2/kg AC. The main contributions to GW were from impregnation, pyrolysis, and drying of the washed ACs. Coconut shell AC is a better option in Malaysia and Indonesia because of the abundant supply of coconuts for feedstock utilization (Iqbaldin et al 2013; Arena et al 2016). Arena et al (2016) reported that the environmental burdens estimated from coconut shell operations could be decreased by 60-80% if a low-carbon electricity system (such as biomass, hydro, or nuclear electricity) were available for the regions. No cradle-to-gate LCA study on AC produced from woody biomass was found in the literature, which is the target area for this analysis (Miller et al 2014, 2015; Gu and Bergman 2016, 2017). In addition, no AC LCA was found that included feedstocks derived from forest or mill residues or using distributed-scale equipment as this project did. This is the first study to quantify environmental impacts of AC derived from thermochemically converting woody biomass and then compare it with commercial coal AC. To compare ACs for the same function, the physical properties of the AC products such as Brunauer–Emmett–Teller (BET) surface area were found. The BET surface area of AC from coconut shells ranges from 1244 to 1769 m^2/g (Iqbaldin et al 2013), compared with 666 m^2/g for coal AC. A recent meta-analysis to evaluate the environmental and economic performance of biochar compared with AC was carried out by Alhashimi and Aktas (2017). They concluded that biochar has lower environmental impact than AC in terms of GHG emissions but similar energy consumption and mixed economic performance.

Unlike previous LCAs conducted by Gu and Bergman (2016, 2017) where the focus was on bioenergy production of the Tucker renewable natural gas (RNG) unit, this project's overall goal was to quantify primary energy consumption and environmental impacts associated with production of biochar AC, including the fossil fuel substitution benefit that biochar AC may provide. Another objective was to assess the potential for maximizing the economic value of biochar. As one would expect, although the life cycle environmental impacts may be proven beneficial for biochar AC, in the end, it is the economics that will drive its production. The price of AC ranges from hundreds to thousands of dollars per metric ton (del-Campo et al 2015), compared with hundreds of dollars or less per metric ton for unprocessed biochar. The price tends to vary based on its absorption properties. Therefore, absorption properties for biochar AC will be analyzed as part of the LCA to match functionality of the two AC systems studied, biochar and coal.

MATERIALS AND METHODS

An LCA was performed from cradle-to-gate for both biochar and commercial coal AC processes to quantify their environmental impacts for a comparative assertion. In this study, biochar from a distributed-scale pyrolysis system, the Tucker

RNG unit, was activated with steam and then examined for its physical and chemical properties including BET surface area and iodine number and then compared with commercial coal AC. The biochar AC model was constructed in three parts: 1) upstream model, forest residue extraction and feedstock processing; 2) mainstream model, woody biomass carbonization; and 3) downstream model, biochar activation (Fig 1). All primary (source) data for the biochar AC was collected and analyzed for each life cycle stage reported here.

Goal and Scope

The cradle-to-gate LCA on AC from biochar made from woody biomass was conducted with a process LCA-based method (ISO 2006a, 2006b). The goal was to quantify the CED and environmental impacts of biochar AC and compare those impacts with the coal AC. To provide a reference point between the two products, a functional unit was used to relate both the environmental inputs and outputs and to quantify the environmental impacts. For this study, the functional unit was 1 kg of AC produced from either biochar or coal with comparable adsorption properties.

The system boundary for this analysis is shown in Fig 1. The study scope covered the system from forest management, extraction of raw materials, which included log harvesting and transportation to the sawmill, feedstock processing, including whole-tree microchipping, screening, and drying, and also the thermochemical conversion (carbonization) and steam activation processes. The thermochemical and activation processes were assumed to be colocated with the feedstock processing facility (ie sawmill). Therefore, no transportation network between chip production, carbonization, and activation was included in this study.

Description of Processes

Production of AC from the processed wood (ie wood chips) included a two-stage operation: carbonization and activation. First, the carbonization

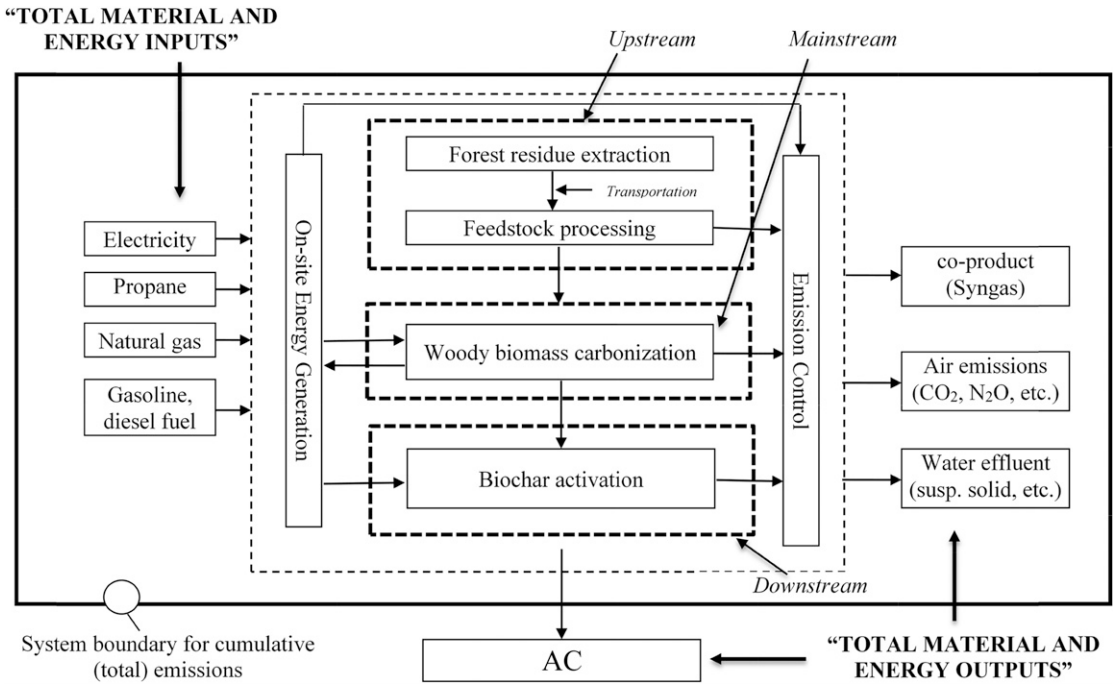


Figure 1. System boundary of activated carbon (AC) produced from forest residues.

process performed at a medium to high temperature (600-1000°C) and in an oxygen-free atmosphere drove off all of the volatile organic compounds and increased the carbon content of the solid (ie biochar). Second, the activation process conducted at an elevated temperature (600-1200°C) in a rotary calciner used an oxidant (steam) to increase the surface area, which simultaneously resulted in mass loss of the incoming biochar. An engineering upscale design of the rotary calciner was developed for the carbon activation process to match the feed of the rotary calciner with the output of the Tucker RNG unit and was part of the analysis.

Feedstock processing and pyrolysis. Biomass feedstocks were obtained from coniferous timber harvested from US National Forests in the states of Montana and Idaho. Lower grade logs were chipped and screened into microchips with a specified dimension less than 13-mm-long and less than 10% moisture content (MC). Wood chip carbonization was carried out in the Tucker RNG system, which was developed and fabricated by Tucker Engineering Associates, Locust, NC. This unit is a distributed-scale advanced biomass pyrolysis system using a high-temperature (>750°C) conversion in an extremely low oxygen environment to convert the biomass feedstock into syngas and biochar. The details of the Tucker RNG system thermochemical conversion process can be found in previous publications (Gu and Bergman 2016, 2017). For this study, the coniferous biomass feedstocks were processed for a 3-min residence time at a temperature of 1000°C and cooled with a water quench. As a BRDI project goal, syngas produced by the Tucker RNG system was used in a generator to produce renewable electricity, with biochar as a coproduct for use either as soil amendment or in AC applications. The biochar bulk density was 260 kg/m^3 at a MC of 58% (including free water) before activation. Figure 2 shows the wood chips, biochar, and AC with proximate and ultimate analysis provided in Table 1.

Carbon activation process. The activation process occurs at a high temperature with steam activation (Azargohar and Dalai 2006; Marsh and Reinoso 2006). A pilot-scale rotary calciner (Fig 3) at the Raymond Bartlett Snow (RBS)-Arvos Group in Naperville, IL, was used for the activation trial of biochar from the Tucker RNG system (Gu and Bergman 2016, 2017). RBS-Arvos typically used the calciner to test different processing conditions for a variety of heat treating applications, including carbon activation. The feed rate was specified by the operating program, based on the feedstock's property and desired ratio of material volume to total calciner volume. The feed rate was set at 1.54 kg/h for a 45-min run and 1.13 kg/h for a 60-min run. The calciner was heated by electric heaters across four temperature zones set at 816°C, 927°C, 927°C, and 927°C, respectively. Superheated steam was injected at the beginning of the chamber. The steam was heated by propane to 550°C. The required volume of steam

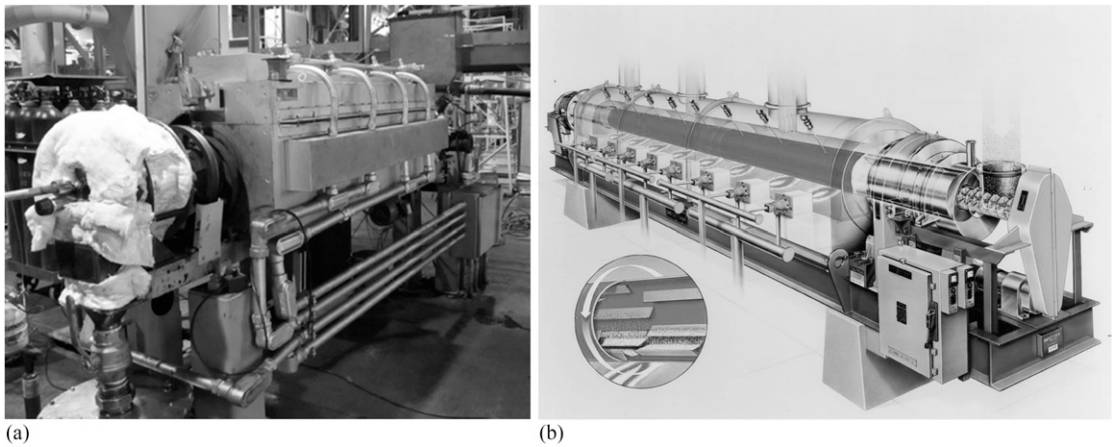
Figure 2. Wood feedstock to final product conversion–(a) microchips made from the wood of coniferous tree species; (b) biochar from wood chips carbonized in a pyrolysis system; and (c) activated carbon made from biochar activated using steam in a rotary calciner.

Table 1. Proximate and ultimate analysis result for the raw material wood chips, feedstock of biochar for carbon activation and final product of activated carbon (AC).

	Proximate material property					
Biomass stage	Fixed carbon (%)	Ash (%)	Volatile (%)	Higher heating value (MJ/kg)		
Wood chip	9.87	0.77	89.36	19.4		
Biochar	78.28	4.30	17.42	31.1		
AC	89.75	5.27	4.98	30.5		
	Ultimate material property					
Biomass stage	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Ash (%)	Oxygen (%)
Wood chip	50.69	6.12	0.15	<0.00	0.77	42.27
Biochar	86.96	2.60	0.12	<0.01	4.30	6.02
AC	91.81	0.46	0.26	0.01	5.27	2.19

was set as the ratio of 1.5 kg for every 1 kg of biochar. A nitrogen purge at the entrance and exit of the chamber prevented ambient air from entering and causing combustion of the biochar. Total nitrogen used was estimated at the rate of 2.89 standard m^3/s for this pilot-scale system.

How emissions from carbon activation were handled and measured was a critical part of finding the environmental impacts. Emissions from the calciner were fully combusted using a thermal oxidizer (ie afterburner) that covered the entire facility, including the calciner used for carbon activation. During the activation process, emission measurement work was conducted by AirTech Inc., Elk Grove Village, IL, which measured and calculated the emissions leaving the reaction chamber and before entering the thermal oxidizer. The filterable particulate matter (PM) and gaseous pollutants in the exhaust system were collected for testing and analysis. The filterable PM concentration was determined using Environmental Protection Agency (EPA) Method 5 (USEPA 1998a) approach. Concentrations of gaseous pollutants in the exhaust gas were determined using EPA Method 320 (USEPA 1998b) with a Fourier transform infrared spectroscopy (FTIR) spectrometer. Because hydrogen and nitrogen cannot be detected with FTIR, tiller bags and metal canisters were used to collect extra exhaust gas for hydrogen and nitrogen analysis. Emissions were reported and summarized based on a mass basis per kilogram of biochar feedstock (Table 2). This emission profile was included in the model when building the biochar AC LCA model with SimaPro 8.2 (PRé Consultants 2017).



(a) (b)

Figure 3. Rotary calciners from Raymond Bartlett Snow (RBS)-Arvos: (a) pilot-scale test calciner and (b) schematic of an upscaled commercial calciner (courtesy of RBS-Arvos).

Table 2. Emission profile measured during the activation of biochar using a rotary calciner.

Substances	kg Per kg of feedstock (biochar)
CO_2	0.856
H_2O	0.043
N_2	0.868
O_2/Oxygen	0.752
H_2/Hydrogen	0.002
CO/Carbon monoxide	0.0042
CH_4/Methane	0.0004
SO_2/Sulfur dioxide	0.0006
HCl/Hydrogen chloride	6.61E-07
NOx/Nitrogen oxide	4.19E-05
N_2O/Dinitrogen monoxide	6.61E-07
C_2H_4O/Acetaldehyde	5.51E-06
C_6H_6/Benzene	3.96E-05
CH_2O/Formaldehyde	2.20E-08
CH_4O/Methanol	2.20E-06
$C_{10}H_8$/Naphthalene	4.41E-06
C_6H_6O/Phenol	9.69E-07
C_3H_6O/Propanal	4.41E-08
Particulates	0.0219

In comparing biochar AC with coal AC with regards to energy consumption and environmental impact, it was assumed that one is a suitable substitute for the other. Following activation, the biochar AC properties were compared with a commercial coal AC widely used for water filtering applications. Two common material properties, iodine number and BET surface area of AC, at room temperature conditions were estimated. The iodine number is defined as the milligrams of iodine adsorbed by one gram of AC, whereas the BET measures the specific surface area of materials to absorb gas molecules on a solid surface. Both the BET surface area and iodine number were higher for the tested biochar AC than for the commercial coal AC. BET surface area was 1092.9 and 666 m^2/g and iodine numbers of 1218 and 847 mg/g for biochar AC and coal AC, respectively, were found. Over the course of the production process and to understand the carbon implications, fixed carbon content increased from 9.87% in the original wood chips to 78.28% in biochar to 89.75% in AC. These results showed that the biochar obtained from carbonization of coniferous wood using the Tucker RNG system is a suitable precursor for the manufacturing of AC marketed for filtration applications and that the LCA comparison here is appropriate.

Upscaled design of rotary calciner. The feeding and reaction capacity of the pilot-scale calciner was very low compared with the upstream biochar output of approximately 33.3 kg/h from the Tucker RNG unit. Therefore, to model the activation process as part of an integrated system, RBS-Arvos Group's engineering team developed an upscaled design of a calciner appropriately sized to the Tucker RNG system. A 60-cm diameter by 4.57-m long heated, gas-fired rotary calciner was proposed by the RBS-Arvos engineers, which was substantially larger than the pilot scale unit (15.2 cm in diameter by 0.9 m long). This design consisted principally of an inclined rotating cylinder housed in a furnace along its active length. The cylinder, indirectly heated, was arranged so that the process off gases and material pass continuously through the unit. For the upscale design, the purge gas was preheated steam and not nitrogen. The gross heat rate for the entire rotary calciner was estimated at 1160 MJ/h fueled by natural gas with a higher heating value of 52 MJ/kg. The steam used for the activation process was estimated at 1 kg of superheated steam (at 900°C) per kg of inputted biochar. Nitrogen was used as the cooler purge gas at the AC discharge. The nitrogen use for the upscaled calciner was estimated from the pilot-scale calciner (15.2 cm in diameter) purge rate, converting to the large commercial calciner (60 cm in diameter). The report from the RBS-Arvos engineering group provided the required engineering estimation of energy consumption, including electricity and natural gas or propane, and material consumption, including nitrogen and steam. See Table 3 for the energy and mass inputs estimated for the upscaled calciner used for the process-based LCA modeling.

Life Cycle Inventory (LCI) Analysis

Using material and energy inputs and reported emissions from the data collection phase, SimaPro 8 LCA modeling software (PRé Consultants

Table 3. Material and energy inputs estimated for upscale rotary calciner.

Input	Unit	Amount
Feedstock—biochar	kg/h	33.60
Nitrogen	kg/h	2.41
Natural gas	m^3/h	36.96
Electricity	kWh	27

2017) estimated the cradle-to-gate LCI of raw material and energy consumption and environmental outputs (flows) on a per-functional-unit basis of 1 kg of AC. All the environmental inputs and outputs are shown in Table 4 for biochar AC and coal AC on a functional unit basis. Primary data for feedstock processing, thermochemical conversion, and final activation were modeled with operational data collected during the processes and with best engineering estimations. Forest management and extraction of logs were modeled using secondary data from the US LCI database (NREL 2012).

Life Cycle Impact Assessment (LCIA)

LCIA integrates the LCI data to quantify the magnitude and significance of potential environmental impacts of a product through its whole life cycle. The environmental impacts were modeled using SimaPro 8 (PRé Consultants 2017) and the tool for the reduction and assessment of chemical and other environmental impacts (TRACI) 2.1 impact method (Bare 2011). TRACI facilitates the characterization of environmental stressors that have potential effects, including ozone depletion (kg CFC-11 eq), GW (kg CO_2 eq), tropospheric ozone (smog) formation (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), human health cancer effects (comparative toxicity unit, CTUh), and human health noncancer effects (CTUh), human health respiratory effects (kg $PM_{2.5}$ eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus).

Assumption and Limitation

Because of incomplete and limited coal AC process data in the publicly available databases and literature, assumptions had to be made to build a relatively complete coal AC LCA model for this study. The main assumption was necessary because of the lack of emission data for the only coal AC model available, which was found in the Agri-footprint database (based on Bayer et al [2005] in SimaPro). To develop a full coal AC model, coal combustion emission data were included.

The emission data for biochar AC was carefully measured at the RBS-Arvos laboratory and then scaled up approximately to the size of the Tucker RNG biochar output based on the RBS-Arvos engineer team's design.

Downstream use and disposal phases (ie gate-to-grave stages) for both AC products were considered the same and thus were not included in the analysis.

Cutoff Rules

If the mass or energy of a flow is less than 0.5% of the cumulative mass or energy of the entire model flow, it may be excluded, provided its environmental relevance is minor. This analysis included all the energy and mass flows for primary data.

RESULTS AND DISCUSSION

The environmental assessment for producing 1 kg biochar AC from new biotechnologies was carried out using LCA and then compared with a commercial coal AC.

LCI for Biochar Activation

With the model outputs from SimaPro, the LCI summarizes all the materials, energy, and cumulated emissions for producing 1 kg of AC from woody biomass residues within the defined system boundary as shown by Fig 1. For the outputs, allocation of the environmental impacts was based on the mass of the two coproducts from the carbonization system, syngas and biochar. The complete emission profile is condensed in Table 5 to show the most notable emissions into air and water. The value of 7.77 kg fossil CO_2/kg AC

Table 4. Complete environmental inputs and outputs for biochar and coal activated carbons (ACs) from cradle-to-gate, on a per kg AC basis.

Biochar AC			Coal AC (with coal combustion emissions)		
Output	Amount	Unit	Output	Amount	Unit
Product			Product		
AC, biochar	1	kg	AC, coal	1	kg
Emission to air			Emissions to air		
Carbon dioxide, biogenic	1.81	kg	Water	12	kg
H_2O/Water	0.09	kg	Acetaldehyde	1.1E-06	kg
N_2/Nitrogen	1.83	kg	Acrolein	1.32E-08	kg
O_2/Oxygen	1.59	kg	Arsenic	3.08E-07	kg
H_2/Hydrogen	0.005	kg	Benzene	0.000284	kg
CO/Carbon monoxide	0.009	kg	Beryllium	2.4E-07	kg
CH_4/Methane	0.001	kg	Cadmium	1.48E-07	kg
SO_2/Sulfur dioxide	0.001	kg	Carbon dioxide, fossil	8.52	kg
HCl/Hydrogen chloride	1.25E-06	kg	Carbon monoxide, fossil	0.002041	kg
NOx/Nitrogen oxide	9.06E-05	kg	Chromium	2.11E-05	kg
Particulates	0.046	kg	Formaldehyde	1.99E-05	kg
C_2H_4O/Acetaldehyde	1.14E-05	kg	Hydrogen fluoride	0.001489	kg
C_6H_6/Benzene	8.56E-05	kg	Lead	8.6E-06	kg
CH_2O/Formaldehyde	2.73E-08	kg	Manganese	2.87E-06	kg
CH_4O/Methanol	4.10E-06	kg	Mercury	2E-06	kg
$C_{10}H_8$/Naphthalene	7.23E-06	kg	Methane, fossil	0.00006	kg
C_6H_6O/Phenol	2.04E-06	kg	Nickel	1.98E-05	kg
C_3H_6O/Propanal	7.14E-08	kg	Nitrogen oxides	0.021362	kg
Emission to water			Particulates, >2.5 μm <10 μm	0.001362	kg
Waste steam	2.11	kg	Particulates, unspecified	0.009672	kg
			Biphenyl	3.75E-05	kg
			Naphthalene	0.000195	kg
			Phenanthrene	1.02E-05	kg
			Selenium	1.95E-06	kg
			Sulfur dioxide	0.136347	kg
			Volatile organic compounds	0.000205	kg
			Emissions to water		
			Oils, unspecified	3.27E-06	kg
			Suspended solids, unspecified	6.55E-06	kg
			Waste to treatment		
			Solid waste, unspecified	0.031947	kg
			Combustion byproducts	0.0408	kg
Input	Amount	Unit	Input[a]	Amount	Unit
Tucker renewable natural gas biochar	2.11	kg	Materials/fuels		
Natural gas	2.33	m^3	Hard coal	3	kg
Nitrogen, liquid	0.15	kg	Drinking water	12	kg
Drinking water	2.11	kg	Transport	0.4	tkm
Electricity, eGrid, NWPP[b] (2008)	1.70	kWh	Electricity/heat		
			Natural gas	3.3	m^3
			Electricity mix, power grid mix EU-27 S, 2014	1.6	kWh

[a] From Bayer et al (2005).
[b] eGrid, Northwest Power Pool (NWPP) is representative of the mix of fuels used for utility electricity in the northwestern US in 2008. The NWPP electricity grid covers an area including Washington, Oregon, Idaho, Utah, most of Montana, Wyoming, Nevada, northern parts of California, Arizona, and New Mexico.

was mainly from the combustion of liquefied petroleum gas (LPG) during the carbonization process and natural gas heating to superheat steam and provide heat for the activation process. A value of 2.57 kg biogenic CO_2/kg AC was estimated with most if not all the emissions occurring upstream during the drying process. With the TRACI method, biogenic CO_2 has a characterization factor of zero; therefore, it does not contribute to the GW impacts shown in this analysis. However, a great deal of debate has occurred regarding this issue of counting biogenic carbon emission in the LCA framework (Sedjo 2013; Miner et al 2014; USEPA 2016). The neutrality of biogenic CO_2 is assumed in this study. Most air emissions came from the activation process. The direct emissions measured for this activation process added important values to the LCI model and LCA result, considering no other research or resource provided such a specific and detailed emission profile. Most water emissions came from fossil fuel extraction and production processes. No specific water emissions were measured from the biomass carbonization and activation process in this study.

Table 5. Life cycle inventory (LCI) flows for activating biochar, cradle-to-gate.

Substance	kg/kg AC
Air emission	
Carbon dioxide, fossil	7.769
Carbon dioxide, biogenic	2.569
Water	2.207
Nitrogen	1.834
Oxygen	1.590
Sulfur dioxide	0.055
Particulates	0.046
Methane	0.032
Nitrogen oxides	0.020
Carbon monoxide, fossil	0.020
Hydrogen	0.005
VOC	0.002
Carbon monoxide, biogenic	0.0014
Nonmethane VOC	0.0011
Sulfur oxides	0.0010
Water emission	
Suspended solids, unspecified	0.411
Chloride	0.373
Sodium	0.105
Solved solids	0.059
Calcium	0.033
Lithium	0.009
Magnesium	0.006
Barium	0.005
Chemical oxygen demand	0.003
Bromide	0.002
BOD5, Biological oxygen demand	0.002
Sulfate	0.0009
Iron	0.0008
Strontium	0.0006
Aluminium	0.0003
Oils, unspecified	0.0002

VOC, volatile organic compounds.

CED

The CED calculated from the cradle-to-gate LCI model outputs are presented in Table 6 for biochar AC. A total CED of 158 MJ/kg biochar AC was required. Natural gas use was the highest energy component representing about 64% of the total CED, followed by crude oil (14%) and coal (8%) for fossil fuel energy. Nonrenewable energy use accounted for 88.8% of the total CED (Table 6), whereas renewable energy accounted for only 11.2% with most from wood and wood waste fuel.

For comparison with alternative commercial AC products on the market, coal AC has been the preferred raw material. However, only one model was found in the Agri-footprint database for coal AC based on Bayer et al (2005). The authors modified the coal AC system by adding the coal combustion emission profile during the activation process. The total CED for coal AC of 242 MJ

Table 6. Cradle-to-gate cumulative energy demand for biochar activation.

Energy sources	Energy MJ/kg AC	%
Natural gas	102.10	64.5
Crude oil	22.63	14.3
Coal, 26.4 MJ per kg	14.49	9.2
Uranium oxide, 332 GJ per kg, in ore	1.37	0.9
Wood and wood waste	17.66	11.2
Storage hydro	0.05	0.0
Other biomass	0.017	0.0
Hydro	0.014	0.01
Wind	0.002	0.00
Total	158.33	100.0
Renewable	17.74	11.2
Non-renewable	140.58	88.8

Table 7. Cradle-to-gate cumulative energy demand for coal activation.

Energy sources	Energy (MJ)/kg AC	%
Coal	85.81	35.5
Uranium	8.21	3.4
Natural gas	142.17	59.0
Crude oil	4.21	1.7
Peat	0.037	0.02
Hydro	0.99	0.4
Wind	0.16	0.1
Solar	0.039	0.02
Geothermal	0.00013	0.0001
Total	241.62	100.0
Renewable	1.37	0.6
Non-renewable	240.25	99.4

was calculated from LCI outputs and is summarized in Table 7 using the model of Bayer et al (2005). Most energy came from natural gas (59.0%) and coal (35.5%), with very limited renewable energy (0.6%) used in the life cycle of coal AC production. CED was decreased by about 35% for biochar AC compared with coal AC, whereas the nonrenewable energy reduction was about 42% (Tables 6 and 7).

Life Cycle Impact Assessment

The cradle-to-gate environmental performance for biochar AC and coal AC are shown in Table 8 for each of the nine impact categories. Total GW potential for biochar AC was calculated at 8.60 kg CO_2 eq/kg AC produced. This is less than half of that for coal AC (18.3 kg CO_2 eq/kg AC produced). The GW potentials of the biochar AC is based on the biogenic carbon neutrality assumption. If biogenic carbon emission (2.57 kg biogenic CO_2/kg AC) is added to the total GW potential, there is still about 39% lower GW potential from biochar AC production than from coal AC production. The GW potential for biochar AC production was mainly from the natural gas use for the carbon activation process, LPG use in the carbonization process, and electricity use for the whole process. Sources contributing to the GW impact are shown in Fig 4 for biochar AC. Coal AC GHG sources were also examined and are shown in Fig 5. Substantial GHG emissions were generated from the coal activation process and also from hard coal processing and electricity use in the whole processes. Most of the other impact indicators, such as ozone depletion, smog, acidification, respiratory effects, and fossil fuel depletion were notably lower for biochar AC than for AC produced from hard coal. Only the eutrophication impact from biochar AC production was higher than that for coal AC production. This was because of nitrogen being used as the purge gas in the biochar activation process, whereas the coal activation process used no nitrogen.

Alternative Scenario Analysis

In the carbonization process, wood chips were pyrolized into syngas and biochar. Biochar was then activated with high-temperature heat and steam in the calciner. The heat was generated using natural gas or electricity in the carbon activation process. However, syngas from the Tucker RNG system could replace natural gas as

Table 8. Comparison of life-cycle environmental impacts for biochar AC and coal AC.

Impact category	Unit	Biochar AC	Coal AC
Ozone depletion	kg CFC-11 eq	2.73E-08	2.44E-07
Global warming	kg CO_2 eq	8.60	18.28
Smog	kg O_3 eq	0.51	0.78
Acidification	kg SO_2 eq	0.070	0.23
Eutrophication	kg N eq	0.277	0.002
Carcinogenics	CTUh	2.87E-08	9.74E-08
Non carcinogenics	CTUh	5.75E-07	2.24E-06
Respiratory effects	kg $PM_{2.5}$ eq	0.004	0.01
Ecotoxicity	CTUe	12.30	11.32
Fossil fuel depletion	MJ surplus	17.09	22.65

AC, activated carbon; CFC, chlorofluorocarbons; CO_2, carbon dioxide; CTU, comparative toxicity unit; N, nitrogen; O_3, ozone; $PM_{2.5}$, particulate matter less 2.5 microns; SO_2, sulfur dioxide.

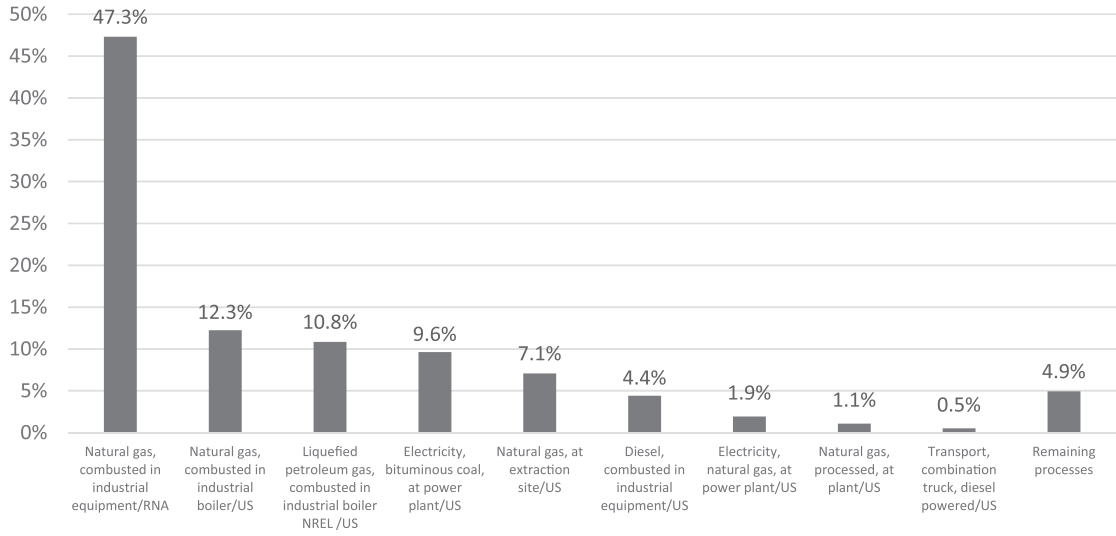


Figure 4. Contribution to global warming potential for cradle-to-gate biochar activated carbon production.

a fuel to heat the calciner instead of generating electricity. Therefore, the scenario assumed a portion of the natural gas used in the activation process was substituted by this syngas. The syngas has a lower heat content (19.7 MJ/m^3) than natural gas (37.7 MJ/m^3). The amount of Tucker RNG syngas needed for biochar activation was calculated based on the total required heat content and the heat content of the syngas. The LCA results for this scenario were compared with the original biochar AC system (Table 9). Using syngas as a substitute resulted in an 11% decrease in GW impact, 50% decrease in respiratory effect (PM count in the air), 31% decrease in fossil fuel consumption, and 28% decrease in acidification. Therefore, substituting natural gas with syngas offers notable environmental impact reductions and ought to be considered during future operations of the biochar AC system.

CONCLUSIONS

Expanding biofuels and bioproducts production using forest biomass as feedstock not only contributes to the development of alternatives with low environmental impacts compared with fossil

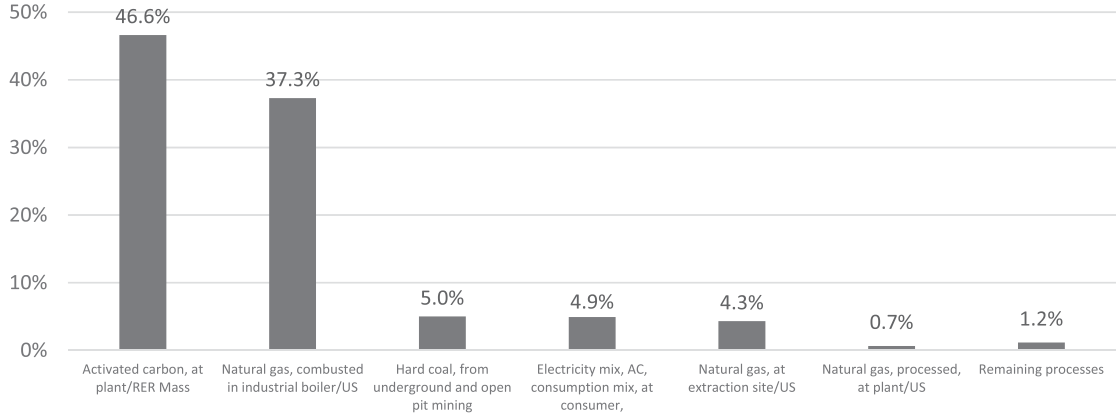


Figure 5. Contribution to global warming potential for cradle-to-gate coal activated carbon (AC) production.

Table 9. Life cycle impact assessment differences when substituting natural gas heating with syngas generated during biochar carbonization process, 1 kg activated carbon (AC).

Impact category	Unit	Biochar AC sub w/tucker renewable natural gas syngas heating	Biochar AC, natural gas heating	Reduction (%)
Ozone depletion	kg CFC-11 eq	7.98E-08	2.73E-08	−192
Global warming	kg CO_2 eq	7.63	8.60	11
Smog	kg O_3 eq	1.13	0.51	−122
Acidification	kg SO_2 eq	0.05	0.07	28
Eutrophication	kg N eq	0.28	0.28	0
Carcinogenics	CTUh	8.41E-08	2.87E-08	−193
Non carcinogenics	CTUh	8.55E-07	5.75E-07	−49
Respiratory effects	kg $PM_{2.5}$ eq	0.0018	0.0037	50
Ecotoxicity	CTUe	15.82	12.30	−29
Fossil fuel depletion	MJ surplus	11.78	17.09	31

CFC, chlorofluorocarbons; CO_2, carbon dioxide; CTU, comparative toxicity unit; N, nitrogen; O_3, ozone; $PM_{2.5}$, particulate matter less 2.5 microns; SO_2, sulfur dioxide; syngas, synthesis gas.

fuels and their associated products but also facilitates forest restoration treatments by providing new markets for woody biomass residues. This study highlighted the environmental performance of such a product, namely biochar AC, along with new biotechnologies of carbonization and activation. As for the environmental performance highlighted in this study, the most notable environmental advantage for biochar AC was the CED reduction and associated GHG emission reduction. In this study, almost 35% less energy was required for cradle-to-gate biochar AC production than for coal AC production. Most fossil energy use for biochar AC came from the carbonization and activation processes with little fossil energy usage coming from upstream feedstock preparation processes. The upstream processes primarily consumed renewable woody biomass energy and woody biomass materials. By contrast, coal AC manufacturing is an almost completely fossil fuel–based production process and uses hard coal as the raw material. The results from this study also showed the total GW potential for wood biochar AC was about half of that for coal AC when biogenic carbon was considered neutral. The GW potential was still 39% lower for this biochar AC than for coal AC even when biogenic carbon was included in the GW potentials. In addition, consuming wood harvested from sustainably managed forests provides notable air quality advantageous by avoiding CO_2 and PM emissions related to burning from natural decomposition of forest-thinning residues and forest fires. As the most recent US forest carbon accounting framework (Woodall et al 2015) reported, forests have many carbon pools that emit carbon through decay and combustion, but they serve a far more active role as a sink of carbon, unlike fossil fuels, which only serve as a carbon emission source. Furthermore, most other life cycle impacts for biochar AC production were lower than those for coal AC. If the carbonization coproduct is used as a fuel substitute for natural gas in the activation process, GW impacts can be reduced further by 11%.

As for the application properties of the AC product, both the BET surface area and iodine number indicated that biochar AC derived from wood is a suitable substitute for commercial coal AC. This demonstrated the feasibility of converting forest and mill residues into the AC product streams for wastewater filtration with the biotechnologies examined in this study. Also in this case, biochar AC is made from renewable and sustainable forest resources, whereas coal AC is made almost entirely from nonrenewable fossil resources. This adds potential benefits for marketing biochar AC as a renewable, sustainable product with better environmental performance than coal AC. Furthermore, this BRDI project explored the pathway from woody biomass residue to AC, with an emphasis on maximizing the economic value of the biomass-to-bioproduct conversion process. The price of AC ranges from hundreds to thousands of dollars per metric ton compared with hundreds of dollars or less per

metric ton for inactivated biochar product. Future economic analysis comparing the biochar AC to coal AC would add more insights for waste stream industries, forest resource management agencies, and policy makers to take action on developing biochar AC.

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