An Introduction to Biochar: Concept, Processes, Properties, and Applications

Jim Amonette
Pacific Northwest National Laboratory
Richland, WA 99352 USA

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Outline

► What is Biochar?
► How is it Made?
  ■ Pyrolysis and Hydrothermal Carbonization Processes
  ■ Feedstocks
  ■ Yields
► What are its Properties?
  ■ Physical
  ■ Chemical
► How can it be Used?
  ■ Energy
  ■ Soil Fertility
  ■ Carbon Sequestration
► Where does it fit in the Environmental Technology Landscape?
► Summary
What is Biochar?

“Biochar is a fine-grained charcoal high in organic carbon and largely resistant to decomposition. It is produced from pyrolysis of plant and waste feedstocks. As a soil amendment, biochar creates a recalcitrant soil carbon pool that is carbon-negative, serving as a net withdrawal of atmospheric carbon dioxide stored in highly recalcitrant soil carbon stocks. The enhanced nutrient retention capacity of biochar-amended soil not only reduces the total fertilizer requirements, but also the climate and environmental impact of croplands.”

(International Biochar Initiative Scientific Advisory Committee)
What is Biochar?

► Product
  ▪ Solid product resulting from advanced thermal degradation of biomass

► Technology
  ▪ **Biofuel**—process heat, bio-oil, and gases (steam, volatile HCs)
  ▪ **Soil Amendment**—sorbent for cations and organics, liming agent, inoculation carrier
  ▪ **Climate Change Mitigation**—highly recalcitrant pool for C, avoidance of N$_2$O and CH$_4$ emissions, carbon negative energy, increased net primary productivity (NPP)
How is Biochar Made?

- **Major Techniques:**
  - **Slow Pyrolysis**
    - traditional (dirty, low char yields) and modern (clean, high char yields)
  - **Flash Pyrolysis**
    - modern, high pressure, higher char yields
  - **Fast Pyrolysis**
    - modern, maximizes bio-oil production, low char yields
  - **Hydrothermal Carbonization**
    - under development, wet feedstock, high pressure, highest “char” yield but quite different composition and probably not as recalcitrant as pyrolytic carbons
Fast Pyrolysis Fluidized Bed Reactor

Brown (2009 in press)
Pyrolysis

- Competition between three processes as biomass is heated:
  - Biochar and gas formation
  - Liquid and tar formation
  - Gasification and carbonization

- Relative rates for these processes depend on:
  - Highest treatment temperature (HTT)
  - Heating rate
  - Volatile removal rate
  - Feedstock residence time
Competition Among Pyrolysis Processes

Factors favoring biochar formation:
- Lower temperature
- Slower heating rates
- Slower volatilization rates
- Longer feedstock residence times

In general, process is more important than feedstock in determining products of pyrolysis.

**Spruce Wood, Slow Pyrolysis, Vacuum (Demirbas, 2001)**

**Eastern Red Maple Wood, Fast Pyrolysis, High Purge Rate (Scott et al., 1988)**
Wood Char Yields from Pyrolysis

Figure from Amonette and Joseph (2009, in press) showing data of Figueiredo et al. (1989), Demirbas (2001), Antal et al. (2000), Scott et al. (1988), and Schenkel (1999) as presented by Antal and Gronli (2003).
Feedstocks

Essentially all forms of biomass can be converted to biochar. Preferable forms include: forest thinnings, crop residues (e.g., corn stover, alfalfa stems, grain husks), yard waste, paper sludge, manures, bone meal. Trace element (Si, K, Ca, P) and lignin contents vary. Lignin content can affect char yields.

![Graph showing Lignin Content, Temperature, and Char Yield](image)

- Linear relationship equation for Husks, Shells, Kernels: $y = 0.39x + 26.76$, $R^2 = 0.99$
- Linear relationship equation for Wood: $y = 0.33x + 15.29$, $R^2 = 0.96$

- Biomass Lignin Content, wt%
- Char Yield, wt%
What are the Properties of Biochar?

Pine Wood Char

Corn Stover Char

Corn Cob Char
Physical Properties Change with HTT

Downie et al., 2009 in press

Kercher and Nagle, 2003
Physical Structure and Chemical Properties Depend on Carbon Bonding Network

Radovic et al., 2001

$^{13}$C CP-MAS NMR
Amonette et al., 2008
Chemical Properties

- Slow Pyrolysis chars produced in presence of steam tend to be acidic (carboxylic acid groups activated)
- Fast Pyrolysis chars produced in absence of steam tend to be very basic and make good liming agents
How can Biochar Technology be Used?

- Generate Carbon-Negative Energy
- Soil Amendment
- Carbon Sequestration
# Comparison of Biochar Production Methods

<table>
<thead>
<tr>
<th>Carbonization Method</th>
<th>Products</th>
<th>Net Energy Released, GJ/t C</th>
<th>Fossil C (Coal) Offset Efficiency</th>
<th>Solid C Production Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Pyrolysis</td>
<td>CH₄, CO₂, Bio-Oils, H₂O, Char</td>
<td>22.0</td>
<td>0.65</td>
<td>0.15</td>
</tr>
<tr>
<td>Slow Pyrolysis</td>
<td>Char, tars, CH₄, CO₂, H₂O</td>
<td>17.7</td>
<td>0.53</td>
<td>0.5</td>
</tr>
<tr>
<td>Hydrothermal Conversion</td>
<td>“lignite”, H₂O</td>
<td>5.5</td>
<td>0.16</td>
<td>1.0</td>
</tr>
<tr>
<td>Combustion</td>
<td>CO₂, H₂O</td>
<td>38.4</td>
<td>0.97</td>
<td>0.01?</td>
</tr>
</tbody>
</table>
The Biofuel N\(_2\)O Problem

- Recent work (Crutzen et al., 2007, Atmos.Chem. Phys. Disc. 7:11191; Del Grosso, 2008, Eos 89:529) suggests that globally, N\(_2\)O production averages at 4% (+/- 1%) of N that is fixed.

- IPCC reports have accounted only for field measurements of N\(_2\)O emitted, which show values close to 1%, but ignore other indicators discussed by Crutzen et al.

- If 4% is correct, then combustion of biofuels except for high cellulose (low-N) fuels will actually increase global warming relative to petroleum due to large global warming potential of N\(_2\)O.

- Biochar avoids this issue:
  - Ties up reactive N in a stable pool
  - Eliminates potential N\(_2\)O emissions from manures and other biomass sources converted to biochar
  - Decreases N\(_2\)O emissions in field by improving N-fertilizer use efficiency and increasing air-filled porosity.
Soil Amendment

- Biochar typically increases cation exchange capacity, and hence retention of $\text{NH}_4^+$, $\text{K}^+$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$
- N from original biomass, however, may not be readily available
- P, on the other hand, is generally retained and available
- Liming agent
- Enhanced sorption of organics (herbicides, pesticides, enzymes) (Good? Bad?)
- Some evidence for increased mycorrhizal populations, rhizobial infection rates
- Used as carrier for microbially-based environmental remediation
- Lowers bulk density
Carbon Sequestration

► Why?

■ Decrease atmospheric GHG levels
■ Stop acidification of oceans by CO$_2$ absorption
■ We only have one Earth

► How?

■ Create stable C pool using biochar
■ Use energy to offset fossil-C emissions
■ Avoid emissions of N$_2$O and CH$_4$
■ Increase net primary productivity (NPP)
Creating a Stable Carbon Pool with Biochar

Current Situation

Net Annual Change: +4.1 Gt

10% Biomass Pyrolysis *

Net Annual Change: -0.7 Gt

*An extreme example based on maximum sustainable biofuel estimates from the IPCC
Human-Appropriated Net Primary Productivity

- 29% of all C fixed by photosynthesis aboveground (ca. 10.2 GtC/yr) is currently used by humans!
- Of this 1.5 GtC/yr is unused crop residues, manures, etc.
- An additional 1.8 GtC/yr is not fixed due to prior human activities (e.g., land degradation) and current land use
- Current fossil-C emissions are ca. 8 GtC/yr
- Increased productivity and expanded use of residues from biochar production could have a significant impact on global C budget

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<table>
<thead>
<tr>
<th>NPP-related carbon flows</th>
<th>Total NPP</th>
<th>Aboveground NPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pg C/yr</td>
<td>%</td>
</tr>
<tr>
<td>Potential vegetation (NPP₀)</td>
<td>65.51</td>
<td>100.0</td>
</tr>
<tr>
<td>Actual Vegetation (NPPₚₑₜ)</td>
<td>59.22</td>
<td>90.4</td>
</tr>
<tr>
<td>Human-induced alteration of NPP (ΔNPPₚₑₜ)</td>
<td>6.29</td>
<td>9.6</td>
</tr>
<tr>
<td>Human harvest (NPPₚₑₜ)</td>
<td>8.18</td>
<td>12.3</td>
</tr>
<tr>
<td>Human-induced fires</td>
<td>1.14</td>
<td>1.7</td>
</tr>
<tr>
<td>Remaining in ecosystem (NPR)</td>
<td>49.90</td>
<td>76.2</td>
</tr>
<tr>
<td>HANPP total</td>
<td>15.60</td>
<td>23.8</td>
</tr>
<tr>
<td>Backflows to nature*</td>
<td>2.46</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Haberl et al., PNAS 2007
Carbon Sequestration using Biochar

- Slow pyrolysis biochars are highly recalcitrant in soils with half-lives of 100-900 years
- Sensitivity analysis suggests that half lives of 80 years or more are sufficient to provide a credible C sink
- Recent evidence using $^{14}$C-labeled biochar shows no evidence for enhanced rates of soil humic carbon degradation in agricultural soils (Kuzyakov et al., 2009)
- No evidence for polyaromatic hydrocarbon (PAH) contamination has been seen
- Down-side risks seem very small
IBI Estimates of Global Biochar Impact

Figure 1. Four sustainable scenarios using carbon-negative biochar technology

Figure 2. Four sustainable scenarios using carbon-negative biochar technology with fossil-C offsets

Figure 3. Cumulative carbon offset predicted by four sustainable scenarios using carbon-negative biochar technology with fossil-carbon offsets

Figure 4. Annual contributions of components of sustainable biochar technology to carbon offsets (2050)
Where does Biochar Fit?

- Offers a flexible blend of biofuel energy, soil fertility enhancement, and climate change mitigation
- Limited by biomass availability and, eventually, land disposal area
- How much biomass can be made available for biochar production vs. other uses?
- Crop-derived biofuels cannot supply all the world’s energy needs
  - **Maximum** estimates suggest 50% of current, 33% of future
  - Biodiversity (HANPP)?
  - N₂O?
- Perhaps best use of harvested biomass is to make biochar to draw down atmospheric C levels and enhance soil productivity, with energy production as a bonus (but not the driving force).
- This will require government incentives (C credits?) and a change in the way we value cropped biofuels
Further Information and Acknowledgments

► International Biochar Initiative (www.biochar-international.org)


► North American Biochar Conference 2009
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References Cited


