Recycling nutrients and carbon from waste-to-fertilizers

Johannes Lehmann
Cornell University
Pyrolysis-Biochar System

- Biomass: manure, organic wastes, bioenergy crops (grasses, willows), crop residues
- Bio-fuel: bio-oil, hydrogen
- Transport
- Energy
- Coproducts (oil, cosmetics)
- Industry
- Residual heat
- Returned to soil as Bio-char

Lehmann, 2007, Frontiers in Ecol Env
Chapter 1: Biochar as a Soil Amendment

**Carbon Product**
- Carbon persistence
- Surface area and functional groups
- Electron shuttle and fused arom.

**Nutrient Product**
- Nutrient enrichment
- Nutrient availability
- Sterilization
- Denaturing of pollutants

**Soil Health**
- GHG reduction + C sequestration
- Pollution reduction by leaching and gas emissions
- Soil remediation
- Inoculant carriers
- Signaling (plant-plant; plant-MO)

**Fertilization**
- Pollution avoidance
Fertilizers from animal residues is NOT New
Pyrolysis Fertilizers are NOT New
Pyrolysis of Slaughterhouse Wastes

P: 8% to 15% (Rock P: 8%; TSP 20%)

Pyrolysis of Slaughterhouse Wastes

No significant different plant P uptake between bone char (RB750) and TSP

Greenhouse trial
Z. mays after five weeks (n=5)
(-RH) without root hairs
(+RH) with root hairs
(+RH +AM) with root hairs and AM inoculants

Zwetsloot et al, 2016, Plant and Soil 408, 95–105
Bone Char as a Fertilizer

Char P has similar effectiveness as commercial P fertilizer

Maize grain yield (t ha\(^{-1}\))

- No additions
- NPK
- NK + P with bone char
- Indigenous fertilizer
- Indigenous fertilizer + biochar

On-farm trials
Ethiopia

(n=10)
Recycling of Dairy Manure using Pyrolysis

No contaminants (heavy metal, PAH, PCB, dioxin/furans, etc.)
No pollutants from manure (pathogens, hormones, antibiotic)
Value as ingredient of potting mix: appr. $1,900 ton⁻¹
83% from non-nutrient value (as potting mix)

Recycling from Urban to Agriculture
Biochar as Adsorber

<table>
<thead>
<tr>
<th>Biochar</th>
<th>Solution</th>
<th>Total N before urine (%w/w)</th>
<th>Total N after urine (%w/w)</th>
<th>ΔN after urine (%w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500°C HSW</td>
<td>Fresh urine + HCl</td>
<td>3.33 ± 0.08</td>
<td>4.47 ± 0.17</td>
<td>1.14 ± 0.19</td>
</tr>
<tr>
<td></td>
<td>Fresh urine</td>
<td></td>
<td>3.59 ± 0.05</td>
<td>0.26 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Deionized water</td>
<td></td>
<td>3.71 ± 0.02</td>
<td>0.38 ± 0.08</td>
</tr>
</tbody>
</table>

- N retention primarily $\text{NH}_4^+$ at pH <7
- Greater than predicted by CEC, 1.14% vs. 0.31% (w/w)
Biochar Oxidation and NH$_3$ Retention

Up to 18% N

Hestrin et al, 2019, *Nature Communications* 10, 664
Biochar Climate Mitigation

Two Entry Points:

A: Soil CDR and emission reduction through pyrolysis:
   - reduce CO$_2$/N$_2$O/CH$_4$ return of the charred OM

B: Soil CDR and emission reduction through soil application:
   - B1: reduce soil GHG emissions (CO$_2$/N$_2$O/CH$_4$)
   - B2: increase CO$_2$ capture by plants through photosynthesis

Lehmann, 2007
Biochar Systems Effects on GHG

Cowie et al., 2015, Earthscan

n=15 studies with 48 scenarios
Chapter 3: Bioenergy Production

GJ per Mg of dry, ash-free feedstock example system based on slow pyrolysis at 450°C followed by tar-cracking at 800°C

Woolf et al. 2014 ES&T 48, 6492-6499
Animal Manure and Energy Generation

125-600 t/yr of poultry litter
Fuel offsets of US$66,000/yr
$480/t biochar at farm gate
Chapter 4: Waste Recycling Systems

- **BIOCHAR SYSTEM**
  - **Biomass Source**
    - Agricultural Waste
    - Fast/Slow Pyrolysis
    - Gasification
  - **Production Technology**
    - Urban Waste
    - Dedicated Feedstock
    - Energy Capture
  - **Soil Application**
    - Soil Characteristics
    - Climate
    - Farming System
New York Phosphate

Dairy Manure: 9,000 tons phosphate per year

Fertilizer sales (2009): 8121 tons phosphate per year
Recycling of Slaughterhouse Waste

Table 1: Total phosphorus in annual bone residues from slaughtered animals in Ethiopia.

<table>
<thead>
<tr>
<th></th>
<th>Total no. of animals (kg per animal)</th>
<th>Bone mass (kg per animal)</th>
<th>% of animals slaughtered (per year)</th>
<th>Bone residues (tonnes per year)</th>
<th>Total phosphorus (tonnes per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cattle</strong></td>
<td>50,283,000</td>
<td>20-30</td>
<td>16-17</td>
<td>160,908-256,447</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sheep</strong></td>
<td>23,642,000</td>
<td>4-5</td>
<td>19-34</td>
<td>17,968-40,192</td>
<td>-</td>
</tr>
<tr>
<td><strong>Goats</strong></td>
<td>22,070,000</td>
<td>4-5</td>
<td>15-30</td>
<td>13,242-33,106</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>95,995,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

17-36k tons P/year

Value of US$ 50-104 million/year

28-58% of annual P imports

Simons et al., 2014, Nature Geoscience 7, 3
Recycling of Slaughterhouse Waste

Collection

1.25 ETB/kg
Average payout 3x daily wage
Amount exceeded capacity
Recycling of Slaughterhouse Waste

Price Comparison of Bone Char Fertilizer with Imported P Fertilizers

Bone Char P Fertilizer is less expensive!

<table>
<thead>
<tr>
<th>Cost scenario</th>
<th>Bone char fertilizer cost</th>
<th>Cost imported equivalent</th>
<th>BC % diff. to imported equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSP Equivalent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low-cost</td>
<td>ETB 5.33</td>
<td>ETB 12.65</td>
<td>-57.89%</td>
</tr>
<tr>
<td>high-cost</td>
<td>ETB 8.42</td>
<td>ETB 12.65</td>
<td>-33.48%</td>
</tr>
<tr>
<td>intermediate</td>
<td>ETB 6.87</td>
<td>ETB 12.65</td>
<td>-45.69%</td>
</tr>
<tr>
<td>DAP Equivalent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low-cost</td>
<td>ETB 8.96</td>
<td>ETB 15.08</td>
<td>-40.56%</td>
</tr>
<tr>
<td>high-cost</td>
<td>ETB 12.13</td>
<td>ETB 15.08</td>
<td>-19.59%</td>
</tr>
<tr>
<td>intermediate</td>
<td>ETB 10.54</td>
<td>ETB 15.08</td>
<td>-30.08%</td>
</tr>
</tbody>
</table>
Recycling of Slaughterhouse Waste

Willingness to pay

Bone Char valued as imported DAP

<table>
<thead>
<tr>
<th>Product</th>
<th>Obs.</th>
<th>Mean Bid</th>
<th>Std. dev.</th>
<th>Median Bid</th>
<th>Mean Bid</th>
<th>Mean price paid</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAP</td>
<td>118</td>
<td>53.04*</td>
<td>31.53</td>
<td>50.00</td>
<td>153.3</td>
<td>122.5</td>
</tr>
<tr>
<td>BoneChar</td>
<td>118</td>
<td>52.02*</td>
<td>30.54</td>
<td>45.00</td>
<td>127.5</td>
<td>107.5</td>
</tr>
<tr>
<td>BoneChar+Urea</td>
<td>118</td>
<td>53.91*</td>
<td>25.44</td>
<td>50.00</td>
<td>111.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*Average bid price is significantly greater than zero at p < 0.01 level
Recycling of Humanure using Pyrolysis

Krounbi et al., 2019, Waste Management 89, 366–378
Take home

1. Recycling options exist for nutrients from wastes

2. Nutrient use efficiency and production costs can be as high as for commercial mineral fertilizers

3. Perceived value to farmers can be as high as for commercial mineral fertilizers

4. Very active field of basic and applied research as well as commercial development
Bedding

https://hoards.com