Prospective life cycle assessment of adipic acid production from forest residue

Matty Janssen, Rio Aryapratama & Anne-Marie Tillman

Division of Environmental Systems Analysis
Department of Energy & Environment
Chalmers University of Technology
Göteborg, Sweden

September 22, 2016
Outline

1. Traditional and alternative production of adipic acid
2. Previous LCAs of adipic acid production
3. Goal and scope of the assessment
4. Results
5. Conclusions
Fossil-based production of adipic acid

- Main application → Production of nylon-6,6
- Traditional production from fossil resources → KA oil\(^1\)

\[
\text{Cyclohexanone} + \frac{1}{2} \text{HNO}_3 \xrightarrow{\text{Cu}^{2+}, \text{V}^{5+}} \text{Adipic acid} + \frac{3}{4} \text{N}_2\text{O} + \frac{3}{4} \text{H}_2\text{O}
\]

\[
\text{Cyclohexanol} + 2 \text{HNO}_3 \xrightarrow{\text{Cu}^{2+}, \text{V}^{5+}} \text{Adipic acid} + \text{N}_2\text{O} + 2 \text{H}_2\text{O}
\]

Bio-based production of adipic acid

- Biorefinery concept for the production of bulk and fine chemicals

**Diagram**

- **Algae**
  - PRETREATMENT/SEPARATION
  - Sugars: Carbon source for fermentation
  - High-value product
  - Algae biomass residues for extraction

- **GROT**
  - PRETREATMENT/SEPARATION
  - Lignin residues
  - Lignin

- **BIOCONVERSION**
  - Adipic acid
  - Lignin derived compound/s
  - Nylon
  - Aromatic chemicals

- **BIOCONVERSION of side streams and nutrient recycling**

**Bulk chemical** → Adipic acid, lignin derivative, e.g. terephthalic acid

**Fine chemical** → Lutein
Previous LCAs of adipic acid production

- ecoinvent process for adipic acid production\textsuperscript{2,3}
  - Global warming $\approx 25$ kg CO\textsubscript{2}-eq/kg adipic acid produced
  - Elimination of N\textsubscript{2}O emissions $\rightarrow$ 75\% reduction of global warming
  - Switch to renewable resource $\rightarrow$ 10\% reduction of global warming

\textsuperscript{3}E. Svensson et al. 10\textsuperscript{th} Conference on Sustainable Development of Energy, Water and Environment Systems. 2015.
Previous LCAs of adipic acid production

- ecoinvent process for adipic acid production\(^2,3\)
  - Global warming \(\approx 25\) kg CO\(_2\)-eq/kg adipic acid produced
  - Elimination of N\(_2\)O emissions \(\rightarrow\) 75% reduction of global warming
  - Switch to renewable resource \(\rightarrow\) 10% reduction of global warming

- Production from cyclohexene using H\(_2\)O\(_2\)\(^4\)
  - Fossil-based feedstock but no use of HNO\(_3\)
  - Global warming \(\approx 6\) kg CO\(_2\)-eq/kg adipic acid produced

- Production from aromatic compounds via fermentation\(^5\)
  - Both fossil-based and bio-based feedstock, no N\(_2\)O emissions
  - Global warming reduction \(\rightarrow\) 9 to 17 kg CO\(_2\)-eq/kg adipic acid produced

---

System description I

Resource extraction, production of auxiliary raw material and energy

- Fuel & electricity production/use
- Chemicals & enzyme production
- Forestry operations

Chemicals & enzyme

- forest residue

Production of adipic acid and co-products

- Feedstock pretreatment
- Adipic acid formation (hydrolysis, fermentation)
- Purification (crystallization)

Supporting activities

- Energy (steam, electricity) production, water use

Reference flow

\( T \) = transport

- Goal → Guide technology development
- Functional unit → 1 kg of adipic acid produced
System description II

- **Pretreatment**
  - Acid-catalyzed → SO₂
  - Alkaline → NaBH₄
- **Additional fuel use** → Fossil, biomass
  - Fermentation yield
  - Concentration of product
System description II

- Pretreatment
  - Acid-catalyzed $\rightarrow$ SO$_2$
  - Alkaline $\rightarrow$ NaBH$_4$

- Additional fuel use $\rightarrow$ Fossil, biomass
  - Fermentation yield
  - Concentration of product

- Lignin use $\rightarrow$ As fuel, as product
System description II

- Soil organic carbon change
- Pretreatment
  - Acid-catalyzed → SO$_2$
  - Alkaline → NaBH$_4$
- Additional fuel use → Fossil, biomass
  - Fermentation yield
  - Concentration of product
- Lignin use → As fuel, as product
Acid-catalyzed pretreatment

- **Bio-based pathway → Significant environmental benefits**
- **Hotspots → Downstream, GROT pretreatment, enzyme**

*Base case - lignin incinerated, fossil fuel for additional energy needs*

Scenario 1 - lignin incinerated, biomass for additional energy needs

Scenario 2 - lignin sold, fossil fuel for additional energy needs

Scenario 3 - lignin sold, biomass for additional energy needs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Alkaline pretreatment

- Higher impacts when compared to the acid pretreatment
- Hotspots → NaBH₄, downstream, GROT neutralization

Base case - lignin incinerated, fossil fuel for additional energy needs
Scenario 1 - lignin incinerated, biomass for additional energy needs
Scenario 2 - lignin sold, fossil fuel for additional energy needs
Scenario 3 - lignin sold, biomass for additional energy needs
NaBH₄ production and use

- Switch to biomass use for energy purposes in NaBH₄ production

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GWP change [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>-22</td>
</tr>
<tr>
<td>1</td>
<td>-32</td>
</tr>
<tr>
<td>2</td>
<td>-19</td>
</tr>
<tr>
<td>3</td>
<td>-32</td>
</tr>
</tbody>
</table>
NaBH₄ production and use

- Switch to biomass use for energy purposes in NaBH₄ production

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GWP change [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>-22</td>
</tr>
<tr>
<td>1</td>
<td>-32</td>
</tr>
<tr>
<td>2</td>
<td>-19</td>
</tr>
<tr>
<td>3</td>
<td>-32</td>
</tr>
</tbody>
</table>

- Change in dosage of NaBH₄ in pretreatment step
SOC change due to adipic acid production

- SOC change over 100 years
- Plant capacity of 100,000 t per year → 2.9 TWh (or $6 \times 10^5$ t) of extra GROT extracted
- Loss of carbon of 3.2 g C (or 11.7 g CO₂) per kg adipic acid

---

Conclusions

- Significant environmental benefit when using to a forest-based feedstock
  - In some cases, worse AP
  - Further improvement by using biomass as an energy source
Conclusions

- Significant environmental benefit when using a forest-based feedstock
  - In some cases, worse AP
  - Further improvement by using biomass as an energy source

- What are the environmental hotspots?
  - Acid-catalyzed pretreatment → Downstream processing, GROT pretreatment
  - Alkaline pretreatment → \( \text{NaBH}_4 \) production and use, downstream processing

- Alkaline pretreatment results in a higher environmental impact
  - Cleaner production of \( \text{NaBH}_4 \) can be achieved
  - Lower usage of \( \text{NaBH}_4 \)
Conclusions

- Significant environmental benefit when using to a forest-based feedstock
  - In some cases, worse AP
  - Further improvement by using biomass as an energy source

- What are the environmental hotspots?
  - Acid-catalyzed pretreatment → Downstream processing, GROT pretreatment
  - Alkaline pretreatment → NaBH₄ production and use, downstream processing

- Alkaline pretreatment results in a higher environmental impact
  - Cleaner production of NaBH₄ can be achieved
  - Lower usage of NaBH₄

- Changes in organic carbon content in the soil due to adipic acid production are small
  - Insignificant climate impact
  - Other impacts?
THANK YOU
Any questions?