LCA and simulation of a bioethanol process technology in development

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Outline

1. Development of a high-gravity biofuels production process
2. Straw-based ethanol production
3. Results for straw-based ethanol production
4. Conclusion
High-gravity production of biofuels

- Second generation biofuels using wood and wheat straw
- Economically feasible process → High gravity fermentation
  - Lower water use
  - Difficulties with mixing
  - High concentrations of end products and inhibitors
High-gravity production of biofuels

- Second generation biofuels using wood and wheat straw
- Economically feasible process → High gravity fermentation
  - Lower water use
  - Difficulties with mixing
  - High concentrations of end products and inhibitors
- Use LCA along the process development path
  - To improve and/or optimize the process from an environmental life cycle point-of-view
  - To help guide the technology development by providing stakeholders the environmental hotspots during all stages
Technology development and scale

- Development "stages" with respect to system boundaries\(^1\)
  - Process step $\rightarrow$ Scale-up of equipment
  - Process complex $\rightarrow$ Optimization of the complete process
  - Value chain $\rightarrow$ Inclusion of the upstream and downstream processes

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\(^1\) M. Shibasaki and S. Albrecht. *Proceedings of European Congress of Chemical Engineering (ECCE-6)*. 2007, p. 5.
Technology development and scale

- Development "stages" with respect to system boundaries
  - Process step → Scale-up of equipment
  - Process complex → Optimization of the complete process
  - Value chain → Inclusion of the upstream and downstream processes

- Time and scale in technology LCA
  - Shifting time frame → Room for technical development, affects performance data, perhaps functional unit
  - Change in background system related to time and scale of penetration

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Process base case and alternatives

- Inbicon's IBUS process\(^3\) in Kalundborg, Denmark
  - Feedstock is wheat straw
  - Hydrothermal pretreatment

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- Industrial-scale evaluation using raw lab data
  - Process calculations done in spreadsheet
  - Experimental set-up → 33 process options
    - Type of enzyme
    - Process configurations
    - Enzyme load
    - Solids content in the reactor
    - Additive to increase enzyme activity

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Inventory analysis for straw-based ethanol production

Cultivation and harvest
Inventory analysis for straw-based ethanol production

Cultivation and harvest

Preparation and pretreatment
- Conditions: \( p=15 \text{ bar}, T=195 \, ^{\circ}\text{C} \)
- Lignin used as energy source
Inventory analysis for straw-based ethanol production

Cultivation and harvest

Preparation and pretreatment
- Conditions: $p=15$ bar, $T=195 \, ^\circ$C
- Lignin used as energy source

Hydrolysis & fermentation
- Differences in conversion efficiency
- Yield as basis for mass balance
Inventory analysis for straw-based ethanol production

Cultivation and harvest

Preparation and pretreatment
- Conditions: $p=15$ bar, $T=195$ °C
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Hydrolysis & fermentation
- Differences in conversion efficiency
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Downstream processing
- Heat duty in distillation varies little at higher ethanol concentration
- Lignin used as energy source
Flow diagram in openLCA

- Impacts calculated for the whole process
Results for 30% dry matter content

**GWP [kg CO₂-eq]**
- Wheat cultivation and harvesting: 50.7
- Straw pretreatment: 61.8
- Chemicals production: 49.2
- Enzyme production: 62.8
- Simultaneous Saccharification and Fermentation (SSF): 37.7
- Pre-Saccharification and Simultaneous Fermentation (PSSF): 45.8

**EP [kg NOx-eq]**
- Wheat cultivation and harvesting: 1.0 × 10⁻²
- Straw pretreatment: 2.0 × 10⁻²
- Chemicals production: 3.0 × 10⁻²
- Enzyme production: 4.0 × 10⁻²

**AP [kg SO₂-eq]**
- Wheat cultivation and harvesting: 5.0 × 10⁻³
- Straw pretreatment: 6.0 × 10⁻³
- Chemicals production: 7.0 × 10⁻³
- Enzyme production: 8.0 × 10⁻³

**POCP [kg ethylene-eq]**
- Wheat cultivation and harvesting: 1.0 × 10⁻¹
- Straw pretreatment: 2.0 × 10⁻¹
- Chemicals production: 3.0 × 10⁻¹
- Enzyme production: 4.0 × 10⁻¹

**Process options**
- PSSF 5 FPU
- PSSF 7.5 FPU
- SHF 5 FPU
- SHF 7.5 FPU
- SSF 5 FPU
- SSF 7.5 FPU

**Process options**
- Wheat cultivation and harvesting
- Straw pretreatment
- Chemicals production
- Enzyme production

SSF - Simultaneous Saccharification and Fermentation
PSSF - Pre-Saccharification and Simultaneous Fermentation
SHF - Separate Hydrolysis and Fermentation
Results for 30% dry matter content, PEG added

- GWP [kg CO$_2$-eq]
- EP [kg NO$_x$-eq]
- AP [kg SO$_2$-eq]
- POCP [kg ethylene-eq]

**Process options:**
- SSF - Simultaneous Saccharification and Fermentation
- PSSF - Pre-Saccharification and Simultaneous Fermentation
- SHF - Separate Hydrolysis and Fermentation

**Values:**
- Wheat cultivation and harvesting
- Straw pretreatment
- Chemicals production
- PEG production
- Enzyme production

<table>
<thead>
<tr>
<th>Process options</th>
<th>GWP</th>
<th>EP</th>
<th>AP</th>
<th>POCP</th>
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<td>PSSF 5 FPU</td>
<td>60.2</td>
<td>1.0×10^-3</td>
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<tr>
<td>SHF 5 FPU</td>
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<td>SHF 7.5 FPU</td>
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Results for 20% dry matter content

- GWP [kg CO$_2$-eq]
  - Wheat cultivation and harvesting
  - Straw pretreatment
  - Chemicals production
  - Enzyme production

- EP [kg NO$_x$-eq]
  - SSF - Simultaneous Saccharification and Fermentation
  - PSSF - Pre-Saccharification and Simultaneous Fermentation
  - SHF - Separate Hydrolysis and Fermentation

- AP [kg SO$_2$-eq]
  - Process options

- POCP [kg ethylene-eq]
  - Process options
GWP, %DM vs. enzyme load vs. yield

![Graph showing GWP, %DM vs. enzyme load vs. yield]
Conclusion

- Related to the case study results
  - Enzyme use has a significant impact
  - Several trade-offs can be identified that influence environmental impact
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  - Enzyme use has a significant impact
  - Several trade-offs can be identified that influence environmental impact

- Related to scale-up
  - Equipment scale-up → Use data of industrial scale processes with similar characteristics
  - Complete system scale-up → Increased use of biomass
  - Level of detail needed at a very early development stage
THANK YOU

Any questions?