INDUSTRY-BASED BIOREFINERIES

Isabel Cabrita
Florbela Carvalheiro, Luís C. Duarte, Francisco Gírio & Rafal Bogel-Lukasik

Seminar on Heat Integration and Biorefineries, IST 2013 July 15th
Concept
Classification
Feedstock Pre-Treatment
R&D Work & Innovation
International Cooperation
Vision of the Future
Heat Integration and Biorefineries 2013 July 15th
Similar to an oil refinery, an industrial plant that converts Renewable Resources - BIOMASS (instead of fossil petroleum) into valuable products.

The biorefinery industrial concept - an integrated process converting biomass available related to the industrial complex into valuable products.
Industry-based Biorefineries

Biorefinery Concept

Energy

Fuels

BIOMASS

PETROLEUM

materials
intermediates
end-products & feedstocks

KEY FACTOR: Sustainability of the RESOURCE supply
Ideal Concept?

– Wide range of valuable products
  • Competitiveness
  • Market

– Ability to process different biomass feedstocks
  • Resources
  • Flexibility
  • Economics

– Efficient integration with minimum impacts
  • Energy
  • Waste
  • Emissions
  • Sustainability
Biorefinery Concept
Conversion routes...

Industry-based Biorefineries

BIOCHEMICAL PLATFORM

THERMOCHEMICAL PLATFORM

EU Biofuels Technology Platform Roadmap

Integrated Biorefinery Complexes

"1st Generation"
Improving existing technologies

"2nd Generation"
Lignocellulosic Biomass & Energy Crops

2020

2010

2005

3rd Generation Biofuels?

2050

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The traditional biochemical path...

Biomass Feedstocks
- Starch
- Hemicellulose
- Cellulose
- Lignin
- Oil
- Protein

Intermediate Platforms
- Biobased Syn Gas
- Sugars
  - Glucose
  - Fructose
  - Xylose
  - Arabinose
  - Lactose
  - Sucrose
  - Starch

Building Blocks
- Building Blocks

Secondary Chemicals
- Secondary Chemicals

Intermediates
- Intermediates

Products/Uses
- Industrial
  - Corrosion inhibitors, dust control, boiler water treatment, gas purification, emission abatement, specialty lubricants, hoses, seals
- Transportation
  - Fuels, oxygenates, anti-freeze, wiper fluids, molded plastics, car seats, belts, hoses, bumpers, corrosion inhibitors
- Textiles
  - Carpets, fibers, ribbons, fabric coatings, foam cushions, upholstery, drapes, ties, sashes
- Safe Food Supply
  - Food packaging, preservatives, terpenes, pesticides, beverage bottles, appliances, beverage can coatings, vitamins
- Environment
  - Water chemicals, flavorants, detergents and soaps
- Communication
  - Molded plastics, computer casings, optical fiber coatings, liquid crystal displays, pens, pencils, inks, dyes, paper products
- Housing
  - Paints, resins, siding, insulation, connectors, coatings, varnishes, floor standards, adhesives, carpeting
- Recreation
  - Footwear, protective equipment, cameras and film, bicycle parts and tires, wet suits, tapes-CO2-DVDs, golf equipment, camping gear, boats
- Health and Hygiene
  - Plastic syringes, condoms, detergents, pharmaceuticals, suntan lotion, medical-dental products, disinfectants, soaps

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BIOREFINERY CONCEPT
The Thermochemical path...

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Pyrolysis

Gasification

Heat Power

Gaseous Fuel

Liquid Hydrocarbons

Chemical Synthesis

Solids

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Biochemical Platform
- Sugar Feedstocks
- Combustible residues
- Combustible streams

Thermochemical Platform
- Fuels, Chemicals & Materials
- Hydrocarbons & Carbonaceous Materials

Heat & Power
- Isabel Cabrita et al.

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Classification of biorefineries depends on complexity and commercial viability

- Biorefinery systems depend on the nature of feedstock and type of conversion process

  - Lignocellulosic Feedstock Biorefinery (LCF - Biorefinery)
  - Whole Crop Biorefinery (WCB)
  - Green Biorefinery (GBR)
  - Two Platform Biorefinery (TPB) to Multi-Platform Biorefinery (MPB)
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Amorphous polymer of phenyl-propene units via co-polymerisation of alcohols (coumaryl, coniferyl and sinapyl alcohols)

Polymer of glucose (C6-sugar) with both crystalline and amorphous regions

Combination of agro-forestry technologies transforming the feedstock to fuels, chemicals and energy.

Amorphous polymer of C5 (xylose) and C6 sugars, and side chains (acetic and uronic acids)

CLASSIFICATION OF BIOREFINERIES
Lignocellulosic Feedstock Biorefinery
CLASSIFICATION OF BIOREFINERIES
Lignocellulosic Feedstock Biorefinery

<table>
<thead>
<tr>
<th>Woody feedstock</th>
<th>Non-woody feedstock</th>
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<tbody>
<tr>
<td>Cellulose</td>
<td>38-50</td>
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<tr>
<td>Hemicellulose</td>
<td>23-32</td>
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<tr>
<td>Lignin</td>
<td>15-25</td>
</tr>
<tr>
<td>Extractives</td>
<td>2-5</td>
</tr>
<tr>
<td>Protein</td>
<td>&lt;0.5</td>
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<tr>
<td>Inorganics</td>
<td>0.1-1</td>
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<tr>
<td>SiO₂</td>
<td>&lt;0.1</td>
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</table>

Hemicellulose and lignin are very significant biomass fractions

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### Polysaccharide type

<table>
<thead>
<tr>
<th>Biological origin</th>
<th>Abrev.</th>
<th>Amount&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Backbone</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Arabinogalactan</td>
<td>AG</td>
<td>1-3;35&lt;sup&gt;*b&lt;/sup&gt;</td>
<td>β-D-Galp</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>α-L-Araf</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>β-L-Arap</td>
</tr>
<tr>
<td>Xyloglucan</td>
<td>XG</td>
<td>2-25</td>
<td>β-D-Glc p</td>
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<td></td>
<td></td>
<td></td>
<td>β-D-Xyl p</td>
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<td></td>
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<td></td>
<td>α-L-Araf</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>α-L-Fuc p</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acetyl</td>
</tr>
<tr>
<td>Galactoglucomannan</td>
<td>GGM</td>
<td>10–25</td>
<td>β-D-Man p</td>
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<td></td>
<td></td>
<td></td>
<td>β-D-Glp p</td>
</tr>
<tr>
<td>Glucomannan</td>
<td>GM</td>
<td>2–5</td>
<td>β-D-Man p</td>
</tr>
<tr>
<td>Glucuronoxylan</td>
<td>GX</td>
<td>15–30</td>
<td>β-D-Xyl p</td>
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<td></td>
<td></td>
<td>Acetyl</td>
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<tr>
<td>Arabinoglucuronoxylan</td>
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<td>5–10</td>
<td>β-D-Xyl p</td>
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<td>β-L-Araf</td>
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<tr>
<td>Arabinoylans</td>
<td>AX</td>
<td>0.15-30</td>
<td>β-D-Xyl p</td>
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<td></td>
<td></td>
<td></td>
<td>Feruloy</td>
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<tr>
<td>Glucuronoarabinoylans</td>
<td>GAX</td>
<td>15-30</td>
<td>β-D-Xyl p</td>
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<td></td>
<td></td>
<td></td>
<td>4-O-Me-α-D-Glc pA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acetyl</td>
</tr>
<tr>
<td>Homoxylans</td>
<td>X</td>
<td>β-D-Xyl&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> % on dry biomass; <sup>b</sup> may also present β-(1→3) linkages on the backbone; * (up to) in the heartwood of larches

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**CLASSIFICATION OF BIOREFINERIES**

Lignocellulosic Feedstock Biorefinery

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**Hemicelluloses**

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CLASSIFICATION OF BIOREFINERIES
Lignocellulosic Feedstock Biorefinery

- Cellulose → Sugars/Glucose
- Hemicellulose → Sugars
- Lignin → Phenolic compounds

Raw Materials:
- Fuels
- Chemicals
- Polymers
- Other materials

Residues:
- Cogeneration (CHP/Heat Power)

Biomass Deconstruction

Heat Integration and Biorefineries 2013 July 15
J.H. Reith et. al., Biorefinery Training Course, 12 June 2009, Ghent:

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LIGNIN origin Potencial products

**Syngas products**
- Methanol
- DME
- Ethanol
- Mixed alcohols
- Fischer-Tropsch
- Liquids
- C1-C7 gasses

**Hydrocarbons**
- Benzene
- Toluene
- Xylene
- Cyclohexane
- Styrenes
- Biphenyls

**Phenols**
- Phenol
- Substituted phenols
- Cathecols
- Cresols
- Resorcinols
- Eugenol
- Syringols
- Coniferols
- Guaiacols

**Oxidised products**
- Vanillin
- Vanillic acid
- DMSO
- Aromatic acids
- Aliphatic acids
- Syringaldehyde
- Aldehydes
- Quinones
- Coniferyl alcohol
- C3-keto adipate

**Macromolecules**
- Carbon fibre fillers
- Polymer extenders
- Substituted lignins
- Thermoset resins
- Composites
- Adhesives
- Binders
- Preservatives
- Pharmaceuticals
- Polyols


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Crops are plants grown in substantial quantities and harvested for food and other purposes.
Biorefinery Feedstocks

- Selective Crops
- Starch, Sugar Crops, Proteins
- Oil, Starch, Sugar Crops, Straw
- Various
- Oil Crops
- Mostly Starch, & Sugar Crops
- Lignocellulosic Crops, Residues, Grasses

Products

- Pharmaceuticals
- Bulk Chemicals
- Fine Chemicals
- Solvents
- Surfactants
- Lubricants
- Polymers
- Fibres

### Classification of Biorefineries

**Whole Crop Biorefinery**

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- **Raw Materials**
  - Fuels
  - Chemicals
  - Polymers
  - Other materials

- **Residues**
  - Cogeneration
  - CHP/Heat Power

**Biomass Deconstruction**

- Cellulose
- Hemicellulose
- Lignin

**WCB**

- Grain
- Oil
- Starch, sugars

- Flour (Meal)

- Straw
  - Lignocellulosic materials
Technological combination to process grass and other immature green biomass into valuable products.

- Juice extraction
- Proteins
- Amino acids’ mixtures
- Sugars
- Lactic Acid

- Solid fraction
- Biogas/Bio-methane
- Fibre materials
- Lignocellulosic material
Biorefinery Platform has been defined as the CONVERSION PATH from raw materials to end-products.

http://www.nrel.gov/biomass/biorefinery.html
CLASSIFICATION OF BIOREFINERIES

Whole Crop Biorefinery

- Grain ('biotechn./chemical' 'physical/chemical')
  - Starch line, Sugar Raw material
- Flour (Meal) 'physical/chemical'
- Cogeneration (CHP) Heat and Power
- Straw ('biotechn./chemical')

Green Biorefinery

- Press Juice 'biochemical' 'biotechnical/physical'
  - Proteins, Soluble Sugars
  - Residues
- Biogas, Cogeneration (CHP) Heat and Power
- Feed, Fuels, Chemicals, Polymers and Materials

Press Cake 'hydrothermal' 'enzymatic' 'thermal chemical'

Cellulose Lignocellulose

Sugar Platform 'biochemical'

- Sugar Raw material
- Sugar Platform 'gasification' 'thermal chemical'

Lignocellulosic Feedstock Biorefinery

- Lignocellulosic Feedstock (LCF)
- Hemicellulose 'biotech./chemical'
- Sugar Raw material
- Cogeneration (CHP) Heat and Power


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Platform could also be associated with:
- Intermediates from raw materials to products;
- Linkages between biorefinery concepts;
- Final Products.

**Objectives**

- Overcome the natural resistance of lignocellulosic feedstocks to microbial degradation
- Reduce the recalcitrance of cellulose and hemicellulose to better enable conversion of the carbohydrates to soluble sugars

**Limitations**

- One of the most expensive processing steps in cellulosic biomass-to-fermentable sugars conversion
- Insufficient separation of cellulose and lignin
- Formation of byproducts (fermentation inhibitors)
- High use of chemicals and/or energy

**Main Pre-treatment Options:**

<table>
<thead>
<tr>
<th>Physical</th>
<th>Chemical</th>
<th>Physico-chemical</th>
<th>Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milling</td>
<td>Acid processes/ Solid (Super) Acids</td>
<td>Autohydrolysis/Liquid hot water</td>
<td>Brown-, white- and soft-rot fungi</td>
</tr>
<tr>
<td>Grinding</td>
<td>Alkaline processes</td>
<td>Steam explosion</td>
<td></td>
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<tr>
<td>Ultrasound</td>
<td>Wet Oxidation</td>
<td>Sub- and supercritical fluids</td>
<td></td>
</tr>
<tr>
<td>Irradiation (microwaves, γ-irradiation)</td>
<td>Organosolv</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ozonolysis</td>
<td></td>
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</tr>
<tr>
<td></td>
<td><strong>Ionic liquids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Inorganic salts</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Solids which can donate protons or accept electrons during reactions

“acids stronger than 100% sulphuric acid” (Brønsted superacids), “acids stronger than anhydrous aluminum trichloride” (Lewis superacids)

Main classes

- **H-FORM ZEOLITES** (*microporous aluminosilicates minerals*)
  - H-mordenite, H-ZSM-5, …, but also bentonite, kaolin

- **TRANSITION-METAL OXIDES** (*mesoporous Single or Mixed metal oxides*)
  - \(\text{Nb}_2\text{O}_5\), \(\text{Zr}\)-TMS, \(\text{TiO}_2\), \(\text{CeO}_2\), \(\text{HNbMoO}_6\), \(\text{Ta}_2\text{O}_5\)-W\(\text{O}_3\), Zn-Ca-Fe oxide, …

- **CATION-EXCHANGE RESINS**
  - Amberlyst-15 (polystyrene-based cation-exchange resin with \(\text{SO}_3\text{H}\)), Dowex 50wx8-100, NKC-9, Nafion® NR50 (perfluorosulfonated ionomer)
Solid (Super) Acids

Compared to liquid catalysts:

- Limited problems associated to equipment corrosion, safety and waste generation
- Easy separation/recovery without loss of activity
- Long catalyst life
- High Selectivity

- Costs
- Reaction time
- Thermal stability
- Water presence can decrease catalytic activity
- Solid-solid interaction required (mass transfer limitations, pore diameters can limit accessibility, …)

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Ionic Liquids (ILS)

- ILs organic salts (melting point < 100ºC)
- High thermal stability, great solvent power, negligible vapour pressure
- Particularly useful in dissolution of cellulose.

  **Imidazolium ILs** dissolve up to 25% of cellulose (Zakrzewska et al., Energ. Fuel, 2010, 24, 737-745), breaking the extensive hydrogen bonding network.

- **Chlorine ILs**; (Cl⁻ strong proton acceptor in the interaction between IL and hydroxyl groups of the carbohydrate). High melting point/viscosity

- **Newly designed ILs** (1-ethyl-3-methylimidazolium dimethylphosphate ([emim][(MeO)₂PO₂]), ILs containing dialkylimidazolium cation and dicyanamide anion)

- Two possible approaches: complete dissolution of biomass followed by selective fractionation (e.g. precipitation) and hydrolysis
FEEDSTOCK PRE-TREATMENT
Physico-Chemical processes

- **Hydrothermal processes**
  - Liquid hot water (LHW) (A)
  - Steam (A)
  - Steam explosion (A)
  - Subcritical water (B)
  - **Supercritical water (C)**

Water ($T_c=374.0^\circ\text{C}, p_c=221.0\text{ bar}$), CO$_2$ ($T_c=31.0^\circ\text{C}, p_c=73.8\text{ bar}$)

- SC water

  Hemicellulose can be completely separated and digestibility of cellulose significantly increased (220$^\circ\text{C}$, $K_w=6.34\times 10^{-12}$, pH =5.5)

- SC CO$_2$

  Significantly increase the digestibility of cellulose (any significant change in microscopic morphology of LCM of biomass). Yield can be enhanced by addition of organic acids (and with SC CO$_2$ the addition of acids is lower)

There is no single method that can fulfill all the requirements for the effective biomass fractionation.

Future: increase in the study of combined/sequential processes targeting separately different fractions.

Milder processes targeting the separation and recovery of hemicellulose and high quality lignin may be advantageous.

Novel processes such as the ones based on ILs, can also be effective, as they may be able to convey the two goals in a single process.

<table>
<thead>
<tr>
<th>Desirable features</th>
<th>Concentrated acid</th>
<th>Dilute acid</th>
<th>Steam explosion</th>
<th>Autohydrolysis</th>
<th>Organosolv</th>
<th>Solid Superacids</th>
<th>Alkaline</th>
<th>Ionic liquids</th>
<th>Supercritical fluids</th>
</tr>
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<tbody>
<tr>
<td>High hemicellulose solubilisation</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
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<tr>
<td>High hemicellulosic monosaccharides production</td>
<td>++</td>
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<td>0</td>
<td>-</td>
<td>-/0</td>
<td>+</td>
<td>-/0</td>
<td>0/+</td>
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<tr>
<td>Low hemicellulosic oligosaccharides production</td>
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<td>0</td>
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<td>-/0</td>
<td>+</td>
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<td>High cellulose recovery</td>
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<td>High chemicals recycling</td>
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<td>n.r.</td>
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<td>-/0/+</td>
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<td>Low corrosion problems</td>
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<td>-</td>
<td>-/0</td>
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<tr>
<td>Low need for chemicals</td>
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<td>-</td>
<td>0</td>
<td>++</td>
<td>-</td>
<td>0/+</td>
<td>-/0</td>
<td>+</td>
<td>++</td>
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<tr>
<td>Low neutralisation requirements</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>n.r.</td>
<td>+</td>
<td>-/0</td>
<td>-/0</td>
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<td>n.r.</td>
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<td>-</td>
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<td>0</td>
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<td>Low operational costs</td>
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<td>0</td>
<td>++</td>
<td>+</td>
<td>-</td>
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<td>- / 0</td>
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<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>+</td>
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</tr>
</tbody>
</table>

Top 12 sugar-derived value-added chemicals (“building blocks”) from biomass

1,4 diacids: succinic, fumaric, malic (C4)
2,5 furan dicarboxylic acid (C6)
3- hydroxy propionic acid (C3)
Glucaric acid (C6)
Itaconic acid (C5)
Levulinic acid (C5)
3-hydroxybutyrolactone (C4)
Aspartic acid (C4)
Glutamic acid (C5)
Glycerol (C3)
Sorbitol (C6)
Xylitol/arabinitol (C5)

Chemistry to Derivatives of Xylitol and Arabinitol

T. Werpy & G. Petersen, “Top Value Added Chemicals From Biomass”, Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas, August 2004, USDOE.
Succinic acid is being increasingly viewed as an intermediate that could lead to various chemicals. Succinic acid is currently manufactured from petroleum through chemical synthesis; it is also possible to produce succinic acid from sugar derived from the hydrolysis of biomass.

Considered from the standpoint of raw material manufacture, it is strongly desired that an economical bioprocess of this type be developed and practically applied.
Heat Integration and Biorefineries


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SCWG – Ideal for wet biomass conversion with much cost and energy associated with drying.

- It eliminates the formation of chars and tars, due to reactions.
- It characterizes incineration.
- It has the advantage of zero NOx and dioxins emission (which characterizes incineration).

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- It characterizes incineration.
- It has the advantage of zero NOx and dioxins emission (which characterizes incineration).

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Main characteristics of the installation
- FB gasifier
  with a square cross sectional area, each side being 0.2 m long and the height 3.7m
- Bed inert material sand
- Gasification medium air/steam; oxygen/steam
- Gasification Temperature 800°C – 900°C
- Catalytic hot gas cleaning system

Fluidised Bed Gasification Installation at LNEG

Feedstocks
Various types of biomass - lignocellulosic wastes, urban wastes, olive bagasse
Mixtures of coal and wastes

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**Industry-based Biorefineries**

**1st Fixed Bed reactor**
- Fuel gas
- Cyclone
- Particulates
- H$_2$S, Tars & Halogens

**2nd Fixed Bed reactor**
- H$_2$ > 50%
- C$_n$H$_m$ very low tar not detected
- NH$_3$, Tars

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International Cooperation and with other Implementing Agreements, namely the Bioenergy, aim at combining the knowledge of industrial technologies with energy efficiency, and the biomass conversion processes...

– Providing a global forum to exchange information, disseminate knowledge gained and lessons learned in an atmosphere that promotes interaction and collaboration
– Encouraging participants to engage in truly collaborative, value-adding research and development of activities and to promote demonstrations
– Focusing the research efforts by regularly updating a prioritized list of research needs and knowledge gaps
– Involving industry and communicating progress apart from industry, government representatives and other appropriate people
ANNEX XI of the IEA Implementing Agreement

INDUSTRY Based BIOREFINERIES
Annex Leader
Isabel Cabrita

FOCUS AREAS

AREA I
Bioenergy
Biofuels
Area Leader: Isabel Cabrita
LNEG

AREA II
Biochemicals
New Fibre Materials
Area Leader: Alexandre Gaspar
RAIZ

AREA III
Sustainability
Integrated Systems
Area Leader: Henrique Matos
IST/UTL

Active Participating countries

Sweden
Belgium
Portugal

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Heat Integration and Biorefineries 2013 July 15th
Participating Entities

– Belgium
  • VITO (Project ALGAECASCAD)
  • WETLANDS (Project Bugworkers)

– Portugal
  • GNIP (Portuguese Group for Process Integration, more directly IST, LNEG and RAIZ)
    (Task management/Projects Bugworkers, ALGAECASCAD, PI in gasification based biorefineries
    and Sustainability methodologies)
  • University of Coimbra (Project on Sustainability methodologies)
  • BIOTREND (Bugworkers)

– Sweden
  • Chalmers University (project PI og gasification based biorefineries)
Technologies

– Biomass gasification, including waste and black liquor gasification
– Pyrolysis
– Biogas production and integration
– Biological conversion
– Combustion
– Gas clean-up processes, including CCS techniques (e.g. using microalgae for CO$_2$ fixation producing hydrocarbons and/or hydrogen)
– Fuels and chemicals synthesis
Programme of Work of Annex XI

- Evaluation of technological and economical options focusing on industry integrated biorefineries
- R&D projects on technology specific areas
- Biorefinery concept with the integration of the capture of CO$_2$ for enhancing the growth of microalgae and/or other biomass species through process integration
- Sustainability and life cycle analysis
Ongoing Projects

Project XI/1 - BUGWORKERS - New tailor-made PHB-based nano-composites for high performance applications produced from environmentally friendly production routes

Project XI/2 - ALGAECASCAD - The biorefinery of Algae

Project XI/4 - Integrated Biofuel Production Processes Based on Systematic Optimization Methodologies

Project XI/5 - Process Integration of Gasification-based Biorefineries
• International cooperation should be strengthened by governments
  – complementarities in targeted actions
  – information management and exchange

• Governments should consider priorities and roadmaps built upon targeted technology or on a mix of technologies
  – integrated multi-disciplinary teams, both of national expertise and foreign identified groups with relevant knowledge on specific needed competences
  – technology transfer
  – incentives for adoption of new technologies

• R&D budgets need to consider a multi-year scheme, with concrete targets

A competitive sustainable component of the World Economy
An example of National Partnership for R&D

Authors: Isabel Cabrita, Ibrahim Gulyurtlu\textsuperscript{a} & M. Nunes da Ponte\textsuperscript{b}, 2012.

\textsuperscript{a} LNEG
\textsuperscript{b} UNL/FCT
- System integration and optimization aspects of pre-treatment, gasification, downstream treatment and end product processing for different technology concepts and products,
- Integration of biomass gasification systems with process industries, district heating systems, industrial clusters, etc.
- Methodologies for assessing technical and economic performance (incl. selection of data) of industrial gasification technologies and systems for different future scenarios regarding energy costs and policy instruments,
- Methodologies for assessing the greenhouse and sustainability impact of products and systems (incl. the generation and selection of data), and
- Case studies
Thank you for your attention