The Use of Renewable Feedstock in Organic Synthesis

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Chemical Biology Course, Seili, Finland
Tuesday, 26 August, 2008

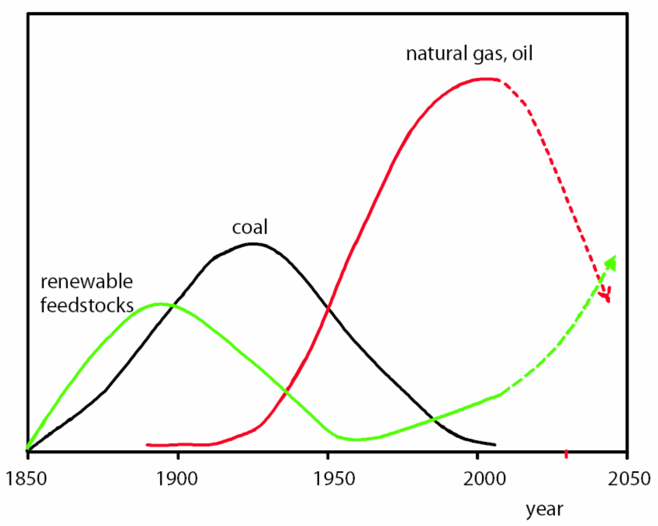
Chem. Eng. News, **86** (23), August 18, 2008: thematic issue on *Sustainability.*

What is sustainable development?

"…sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

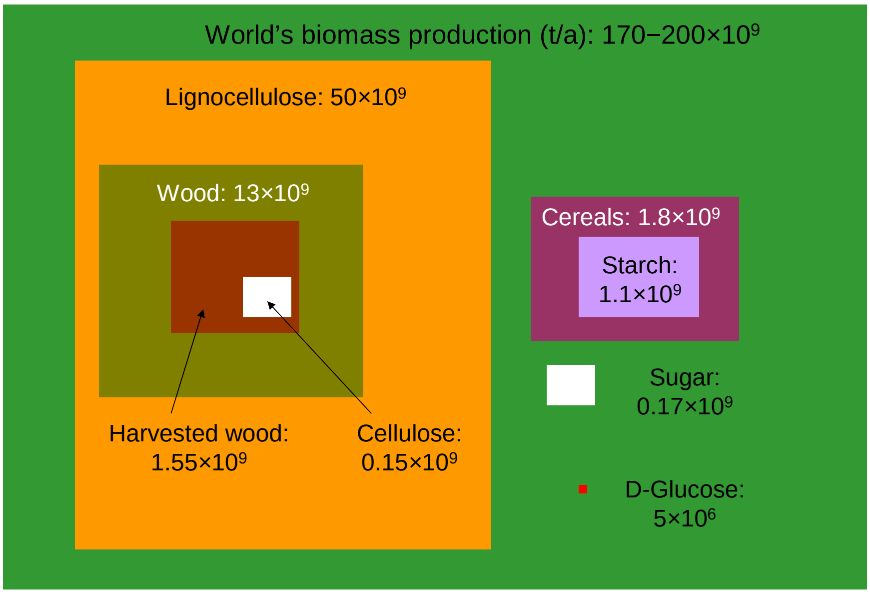
Brundtland Commission (1987): Our common future

Raw materials basis of chemical industry in a historical perspective

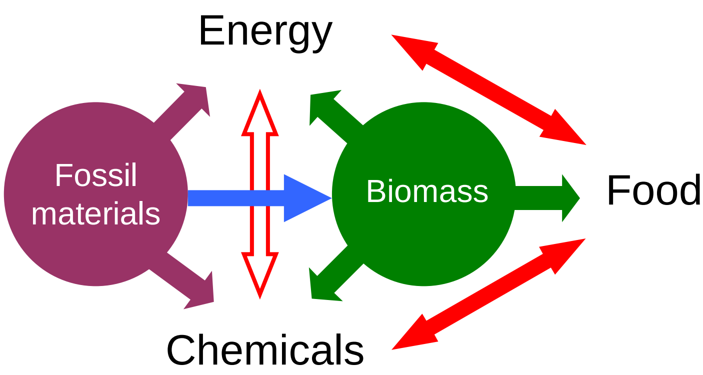


F.W. Lichtenthaler, S. Peters, *C. R. Chimie*, 2004, **7**, 65-90.

The amount and nature of annually produced biomass

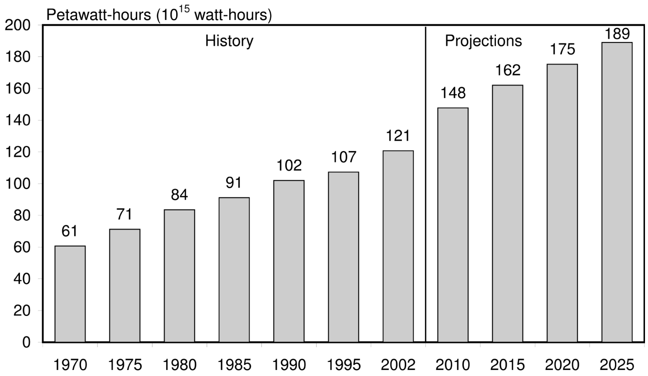


Paradigm shift and the ensuing conflicts



- increasing use of biomass instead of fossil materials
- potential competition between food, energy crops for land use and carbon-based consumer products (chemicals)

The World’s primary energy consumption, 1970 to 2025

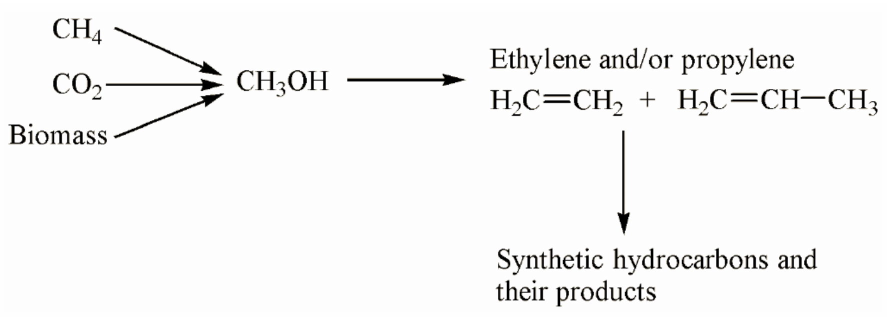


G. A. Olah, A. Goeppert, G. K. S. Prakash: *Beyond Oil and Gas: The Methanol Economy*, Wiley-VCH, Weinheim, 2006

“The generation, storage, and transport of energy are among the greatest challenges, if not the most formidable challenge at all, for years to come.”

A. Taubert, Guest Editor, in his Editorial for the special issue of *International Journal of Molecular Sciences* devoted to "Energy Technology for the 21st Century - Materials and Devices“, 2008, http://www.mdpi.org/ijms/specialissues/energytec.htm

Oláh’s proposed solution: the methanol economy®



G. A. Olah, A. Goeppert, G. K. S. Prakash:
Beyond Oil and Gas: The Methanol Economy, Wiley-VCH, Weinheim, 2006

Challenges for a sustainable development

Replacement of fossil fuels for energy

Hydrogen economy (generation, storage, and transportation of H_2), solar power

Sustainable liquid (methanol, ethanol, *etc.*) economy

Production of carbon based consumer products from renewable resources

Cheap H_2

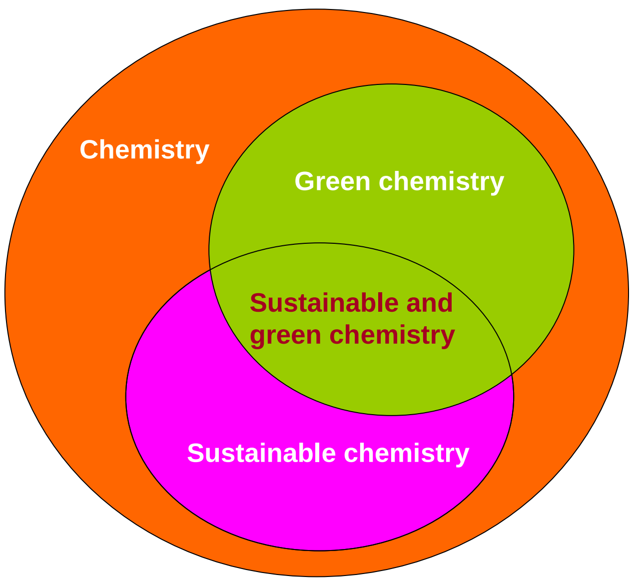
Carbon dioxide (CO_2)

Biomass ← **Using Nature for CO_2 conversion**

Molecular level understanding of pollution prevention

Green chemistry

Sustainable and green chemistry



The principles of sustainable/green chemistry

Green chemistry is the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture, and applications of chemical products.

1. **It is better to prevent waste than to treat or clean up waste after it is formed.**
2. **Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.**
3. **Wherever practicable, synthetic methodologies should be designed to use and generate substances that process little or no toxicity to human health and the environment.**
4. **Chemical products should be designed to preserve efficacy of function while reducing toxicity.**
5. **The use of auxiliary substances (*e.g.* solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used.**
6. **Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.**

Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998

The principles of sustainable/green chemistry

(continued)

7. **A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable.**
8. **Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.**
9. **Catalysts (as selective as possible) are superior to reagents.**
10. **Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.**
11. **Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.**
12. **Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosion, and fires.**

Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998

Fossil vs. renewable materials

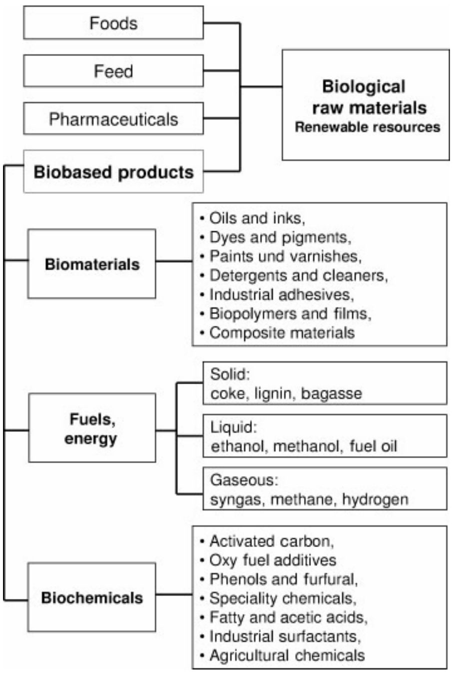
- Fossil (depleting) materials (petroleum oil, natural gas, tar-sand, shale bitumen, coals) are mixtures of hydrocarbons. When oxidized (combusted) they form carbon dioxide (CO_2) and water (H_2O) and thus are not renewable *on the human scale*.

- Renewable feedstocks (biomass), in contrast, will re-grow annually. They are much more varied in their composition (carbohydrates, vegetable oils and animal fats, terpenes, lignins *etc.*). As a rule, they are usually more oxygenated than their fossil counterparts.

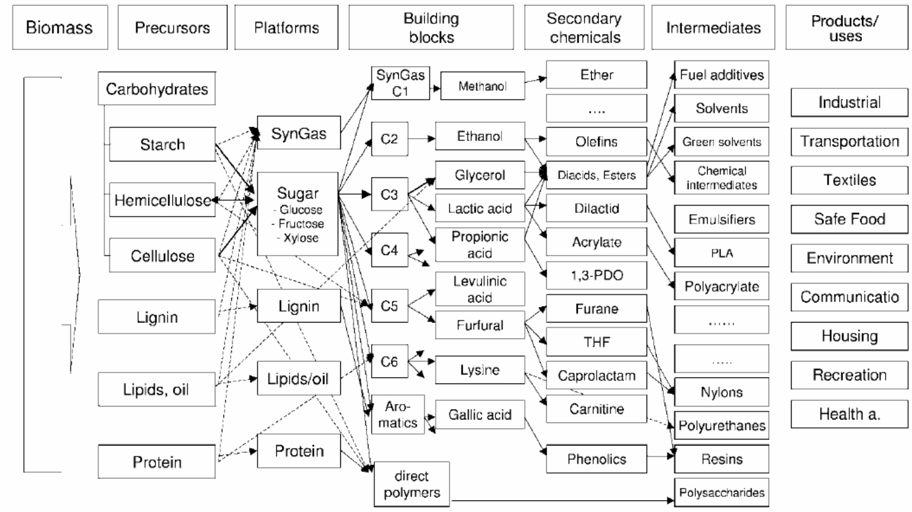
Biomass use in more detail

"The term "biomass" means any organic matter that is available on a renewable or recurring basis (excluding old-growth timber), including dedicated energy crops and trees, agricultural food and feed crop residues, aquatic plants, wood and wood residues, animal wastes, and other waste materials."

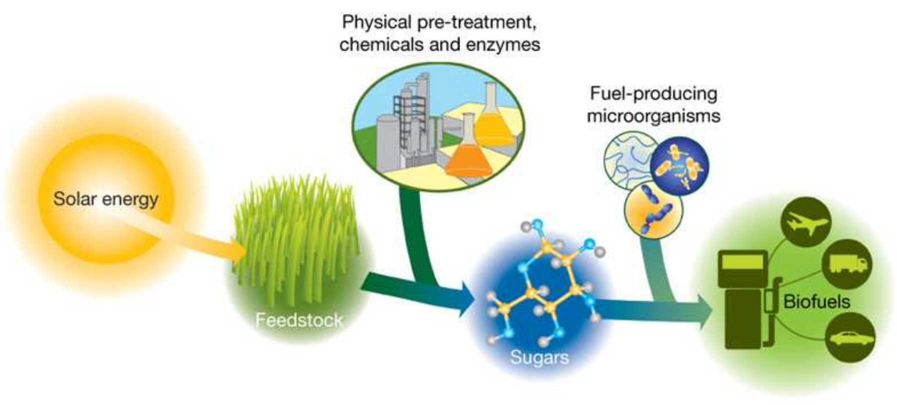
B. Kamm, P. R. Gruber, M. Kamm (2005): Biorefineries – Industrial Processes and Products, in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, Vol. 4, p. 101-133.



Model of a product flow-chart for biomass feedstock



Biology of bioconversion of solar energy into biofuels

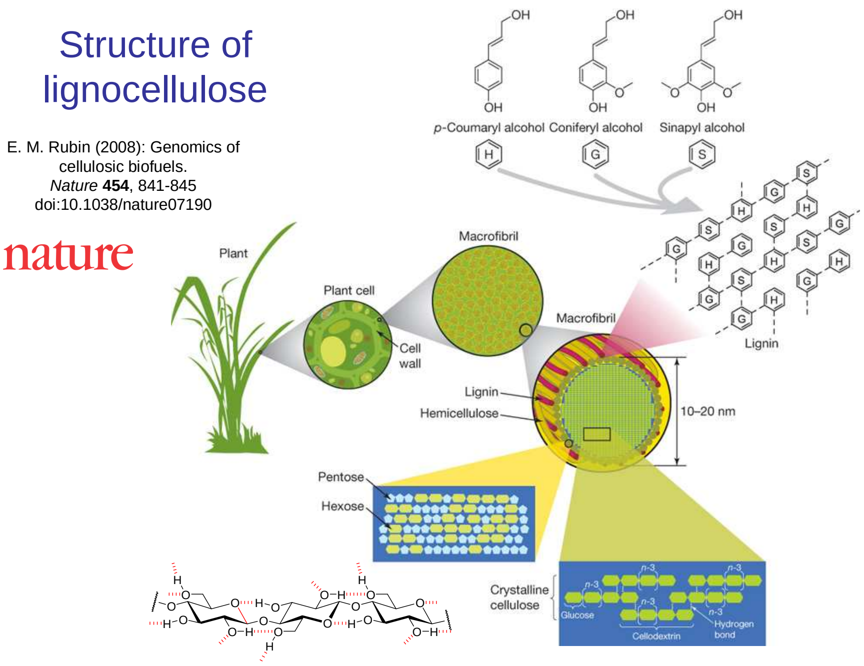


E. M. Rubin (2008): Genomics of cellulosic biofuels. *Nature* **454**, 841-845 doi:10.1038/nature07190

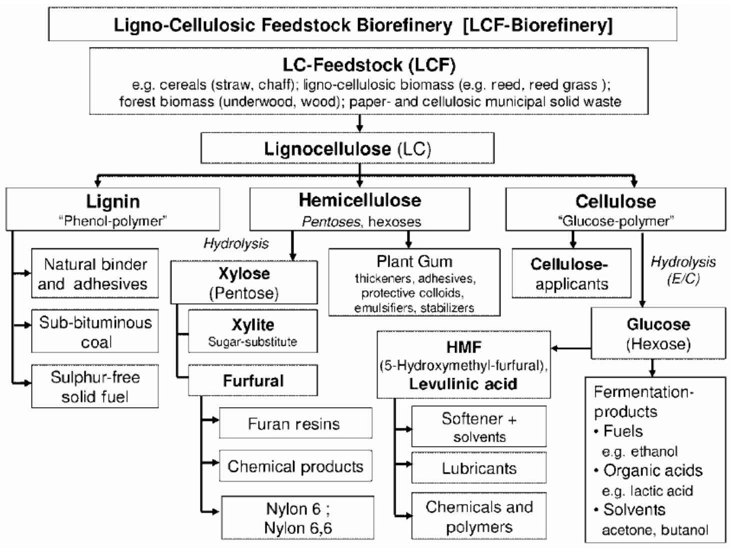
nature

Structure of lignocellulose

E. M. Rubin (2008): Genomics of cellulosic biofuels.
Nature **454**, 841-845
doi:10.1038/nature07190



Products of a lignocellulosic feedstock biorefinery

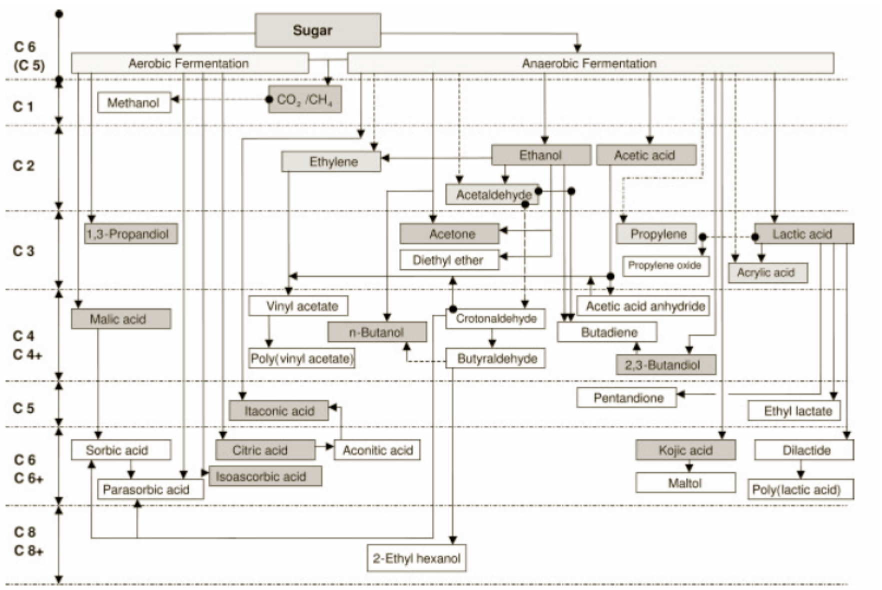


The major biomass components as a renewable feedstock for the chemical industry

- Carbohydrates (cellulose, hemicellulose *etc.*) 75 %
- Lignin 20 %
- Proteins, nucleic acids, fats and oils, terpenes, alkaloids *etc.* 5 %
- Only 3 to 3.5 % (ca. 6×10^9 t) of this amount is used in non-food applications, *e.g.* chemistry

A. Corma, S. Iborra, A. Velty (2007): Chemical routes for the transformation of biomass into chemicals. *Chem. Rev.*, **107**, 2411-2502.

Biotechnological sugar-based product family tree



The use of carbohydrates: pros and cons

- inexpensive materials
- available from virtually inexhaustible, renewable sources
- they are rich in chiral centers

- too many hydroxyl groups
  - most often protecting groups are required
- too many chiral centers
- too few reactive functional groups (C=C, C=O)
- the price of more complex carbohydrates has not been competitive with petrochemicals for a long time

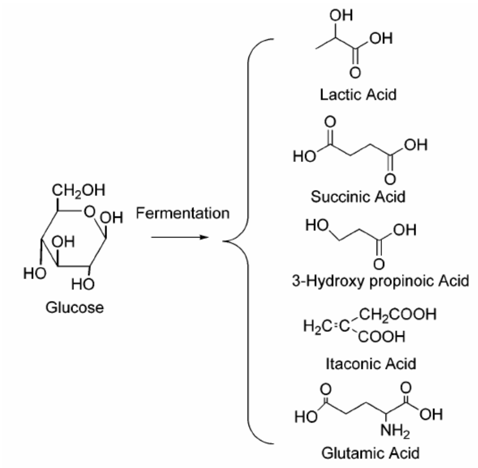
Carbohydrates: major transformation pathways

- Chemicals from Fermentation Processes: Glucose Fermentation
  - Lactic Acid Platform
  - Succinic Acid Platform
  - 3-Hydroxypropionic Acid Platform
  - Itaconic Acid Platform
  - Glutamic Acid Platform
- Chemical Transformations of Monosaccharides
  - Dehydration of Monosaccharides
- Chemical Transformation of Disaccharide (Sucrose etc.)
  - Hydrolysis
  - Esterification
  - Etherification
  - Oxidation
  - Glucosyl Shift: Production of Isomaltulose and Isomalt
  - Polymers
- Polysaccharides
  - Depolymerisation
  - Deacetylation of Chitin

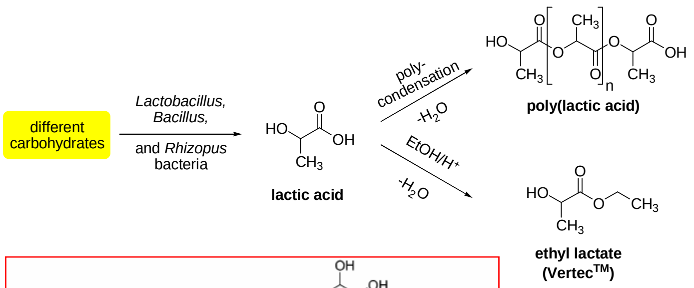
Glucose fermentation and oxidation

	ΔG (kcal/mol)
$C_6H_{12}O_6 + 2\ P_i + 2\ ADP \rightarrow 2\ CH_3CH(OH)COOH + 2\ H_2O + 2\ ATP$	–47
$C_6H_{12}O_6 + 2\ P_i + 2\ ADP \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 + 2\ H_2O + 2\ ATP$	–47
$C_6H_{12}O_6 + 6\ O_2 + 36\ P_i + 36\ ADP \rightarrow 6\ CO_2 + 42\ H_2O + 36\ ATP$	–680

other fermentation processes

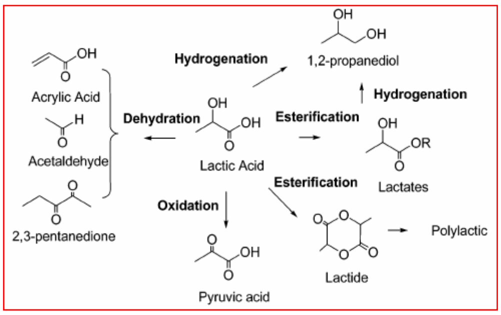


Principal applications of lactic acid



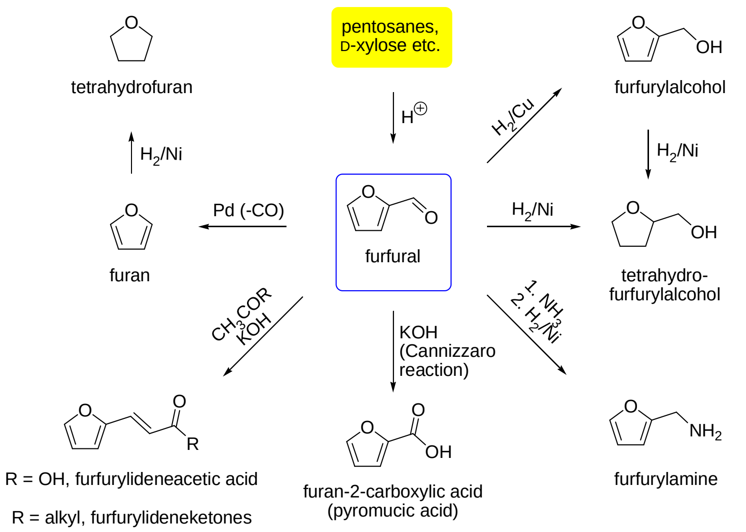
biodegradable polymer
> 140 000 t/a

environmentally benign solvent, replacement of DMF, *N*-methyl-pyrrolidone, acetone, toluene

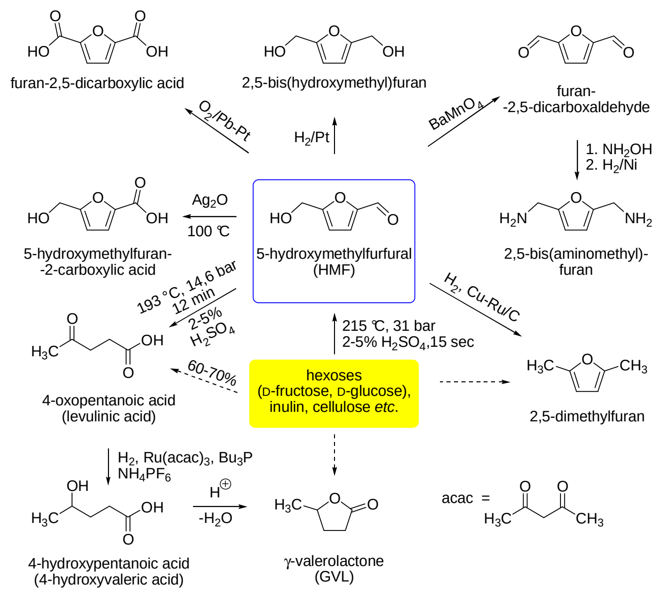


other uses of lactic acid

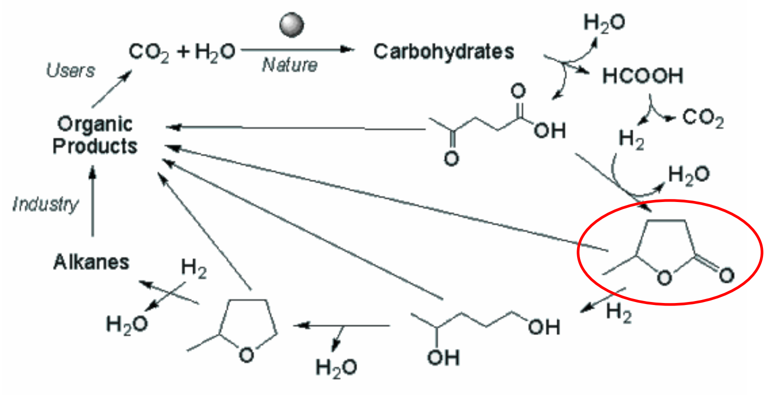
The furan platform: furfural



The furan platform: 5-hydroxymethylfurfural 1.



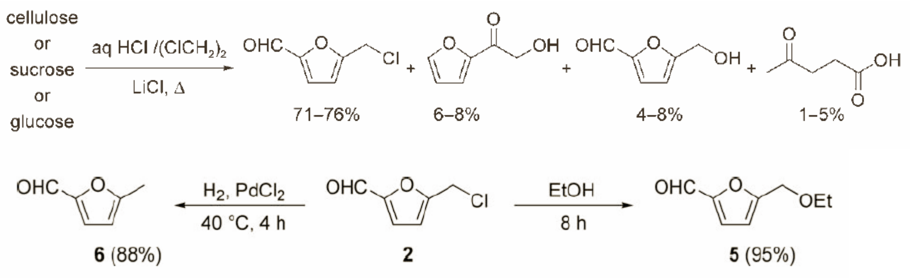
γ-Valerolactone (GVL) from biomass



Research octane number (RON): 130

I. T. Horváth, H. Mehdi, V. Fábos, L. Boda, L. T. Mika (2008): γ-Valerolactone - a sustainable liquid for energy and carbon-based chemicals. *Green Chem.*, **10**, 238-242.

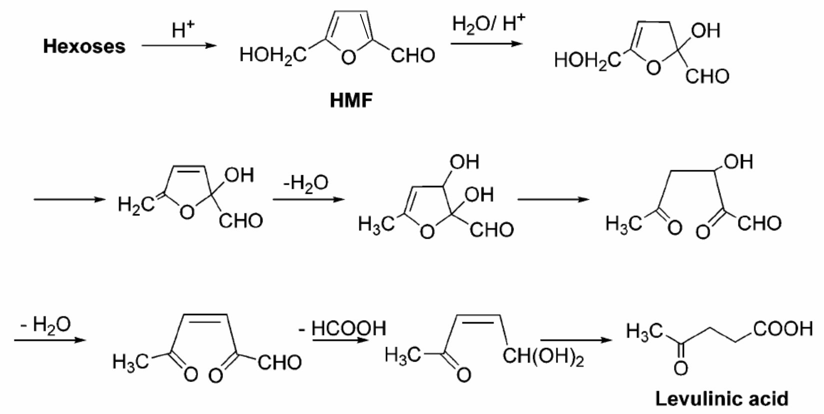
The furan platform: 5-hydroxymethylfurfural 2.



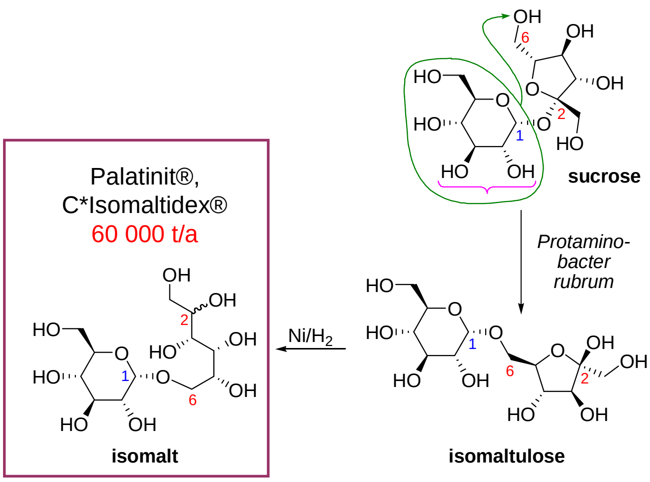
energy density (kWhL^{-1})
5-ethoxymethylfurfural (EMF): 8.7
ethanol: 6.1
gasoline: 8.8
diesel fuel: 9.7

M. Mascal, E. B. Nikitin, *Angew. Chem. Internatl. Ed. Engl.* (2008): Direct, high-yield conversion of cellulose into biofuel, **47**, published online: Aug 1 2008 4:00AM, DOI: 10.1002/anie.200801594.

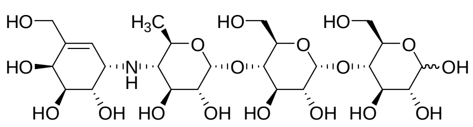
Dehydration of monosaccharides to furans and levulinic acid



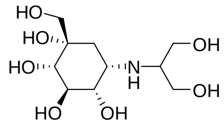
Glucosyl shift: production of artificial sweeteners isomaltulose and Isomalt



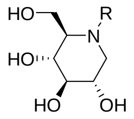
Glycosidase inhibitors used as drugs



acarbose
(Glucobay®/Precose®/Prandase®)

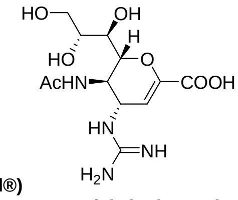


voglibose
(Basen®/AO-128/Volix)

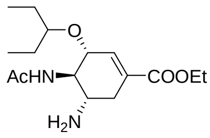


R = CH_2CH_2OH
miglitol (Glyset®/Diastabol®)

R= *n*-Bu
***N*-butyldeoxynojirimicin**
(miglustat/Zavesca®)

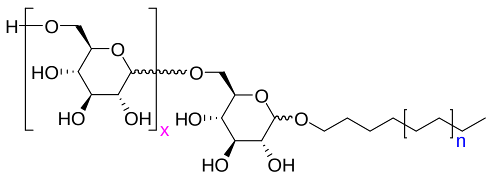


Zanamivir (Relenza®)



oseltamivir (Tamiflu®)

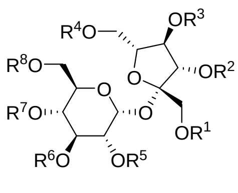
Other industrial carbohydrate-based products



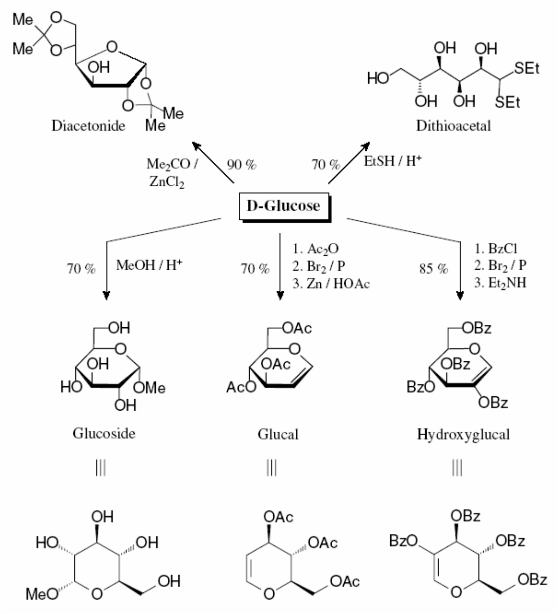
alkyl polyglucosides (APG)
x = 0.3-0.7; n = 1-5

surfactants
50,000 t/a

fat replacer (‘fatless’ fat)
dioxin sequestrant



Olestra (Olean®)
$R^1 \cdots R^8$ = fatty acyl$_{6-8}$/H$_{2-0}$



D-Glucose derivatives as versatile building blocks

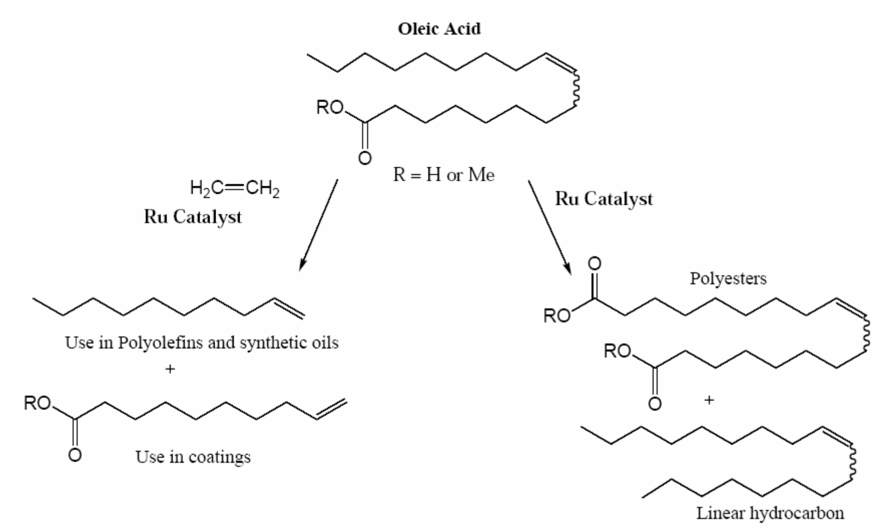
F. W. Lichtenthaler, S. Peters (2004): Carbohydrates as green raw materials for the chemical industry. *C. R. Chimie* **7**, 65-90.

Vegetable oils, waxes and animal fats

- Reaction of the Carboxy Group
  - Fatty Acids
  - Fatty Amines
  - Fatty Alcohols
  - Glycerol
- Reaction of the Fatty Chain
  - Epoxidation
  - Ring-Opening of Epoxidized Fatty Acid Derivatives
  - Hydroformylation
  - Dimerization
  - Oxidative Cleavage and Ozonolysis
  - Metathesis Reactions

Picture © Craig Blacklock

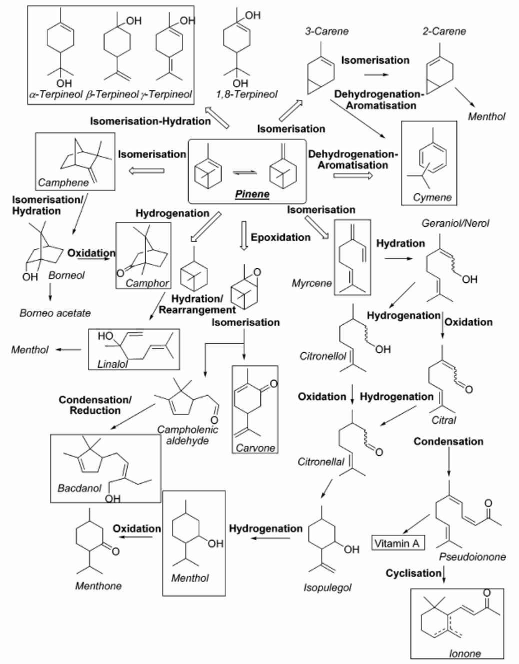
Oleic acid to value added chemicals from metathesis reactions



Terpenes

- Pinene
  - Isomerization: α-Pinene
  - Epoxidation of α-Pinene
  - Isomerization of α-Pinene Oxide
  - Hydration of α-Pinene: α-Terpineol
  - Dehydroisomerization
- Limonene
  - Isomerization
  - Epoxidation: Limonene Oxide
  - Isomerization of Limonene Oxide
  - Dehydroisomerization of Limonene and Terpenes To Produce Cymene
- Carene
  - Isomerization of Carene
  - Epoxidation of Carene
  - Isomerization of 2- and 3-Carene Oxides
  - Dehydroisomerization
- Camphene
  - Epoxidation of Camphene
- Citral
  - Aldol Condensations of Citral and Ketones
  - Baeyer-Villiger Oxidation: Melonal
  - Hydrogenation of Citral

Picture © Wikipedia



Some valuable compounds that can be obtained from α- and β-pinene

Vitamin A acetate:
> 3,000 t/a

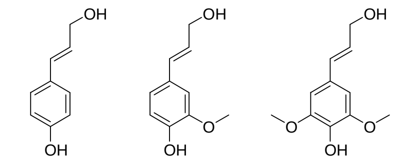
Lignins

- Production of dimethylsulfoxide from lignins
- Synthesis of vanillin

Picture © Craig Blacklock

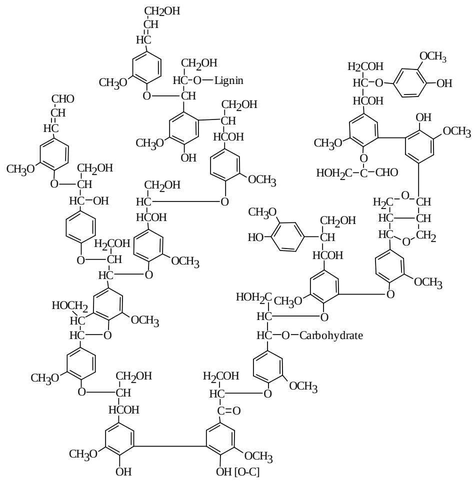
The structure of lignins

- Main components (monomers)



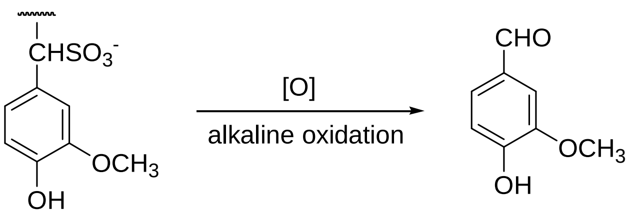
p-coumaryl alcohol   coniferyl alcohol   sinapyl alcohol

- Partial structure of a lignin polymer

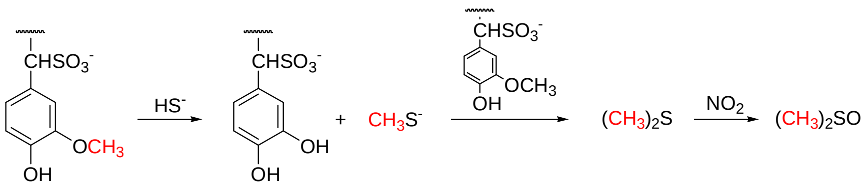


Vanilin from lignin

- As of 2001, the annual demand for vanillin was 12,000 tons, but only 1,800 tons of natural vanillin were produced
- Except for the early times, synthetic vanilin is produced from petrochemical sources (eugenol or guaiacol)
- Vanilin is also produced from waste sulfite liquors from the cellulose industry by alkaline oxidation
- In the traditional process, >160 tons of caustic waste are produced for every ton of vanillin manufactured



DMSO from lignine



Lignosulfonates act as methylating agents

Selected readings 1. Books

- R. J. Simmonds (1992): *Chemistry of biomolecules: an introduction.* Royal Society of Chemistry, Cambridge.
- B. G. Davis, A. J. Fairbanks (2002): *Carbohydrate chemistry.* (Series Ed: S. G. Davies. Oxford Chemistry Primers, 99.) Oxford University Press, Oxford.
- J. F. Robyt (1998): *Essentials of carbohydrate chemistry.* (Series Ed: C. R. Cantor. Springer advanced texts in chemistry.) Springer Verlag, New York.
- P. M. Collins, R. J. Ferrier (1996): *Monosaccharides. Their chemistry and their roles in natural products.* John Wiley and Sons, New York.
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- M. Bols (1996): *Carbohydrate building blocks.* John Wiley and Sons, New York.
- J. N. BeMiller, R. L. Whistler, Eds. (1992): *Industrial gums: polysaccharides and their derivatives.* Academic Press.
- G. A. Olah, A. Goeppert, G. K. S. Prakash (2006): *Beyond oil and gas: the methanol economy*, Wiley-VCH, Weinheim.
- F. Gunstone (2004): *The chemistry of oils and fats: sources, composition, properties and uses.* Wiley-Interscience, New York.
- F. Shahidi Ed. (2005): *Bailey's industrial oil and fat products.* Volumes 1-6, 6th Edition, Wiley-Interscience, New York.
- M. Pagliaro, M. Rossi (2008): *Future of glycerol. New usages for a versatile raw material.* Royal Society of Chemistry, Cambridge.
- T.-L. Ho (1992): *Enantioselective synthesis: natural products from chiral terpenes.* Wiley-Interscience, New York.
- E. Breitmaier (2006): *Terpenes: flavors, fragrances, pharmaca, pheromones.* Wiley-VCH, Weinheim.
- P. T. Anastas, R. H. Crabtree Eds. (2008): *Handbook of green chemistry - green catalysis*. Wiley-Interscience, New York.
- R. A. Sheldon, I. Arends, U. Hanefeld Eds. (2007): *Green chemistry and catalysis*. Wiley-Interscience, New York.
- P. Tundo, A. Perosa, F. Zecchini Eds. (2007): *Methods and reagents for green chemistry: an introduction.* Wiley-Interscience, New York.

Selected readings 2. Reviews, papers and websites

- A. Corma, S. Iborra, A. Velty (2007): Chemical routes for the transformation of biomass into chemicals. *Chem. Rev*., **107**, 2411-2502. See other papers in the same issue as well.
- J. Szejtli (2004): Past, present, and future of cyclodextrin research. *Pure Appl. Chem.* **76**, 1825-1845.
- F. W. Lichtenthaler, S. Mondel (1997): Perspectives in the use of low molecular weight carbohydrates as organic raw materials. *Pure Appl. Chem.* **69**, 1853-1866.
- F. W. Lichtenthaler (2002): Unsaturated *O*- and *N*-heterocycles from carbohydrate feedstocks. *Acc. Chem. Res.*, **35**, 728-737.
- F. W. Lichtenthaler, S. Peters (2004): Carbohydrates as green raw materials for the chemical industry. *C. R. Chimie* **7**, 65-90.
- F. W. Lichtenthaler (2005): Carbohydrates in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, Vol. 5, p. 79-122.
- I. T. Horváth, H. Mehdi, V. Fábos, L. Boda, L. T. Mika (2008): γ-Valerolactone - a sustainable liquid for energy and carbon-based chemicals. *Green Chem.*, **10**, 238-242.
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