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Challenges and Opportunities for the Integrated Forest Biorefineries

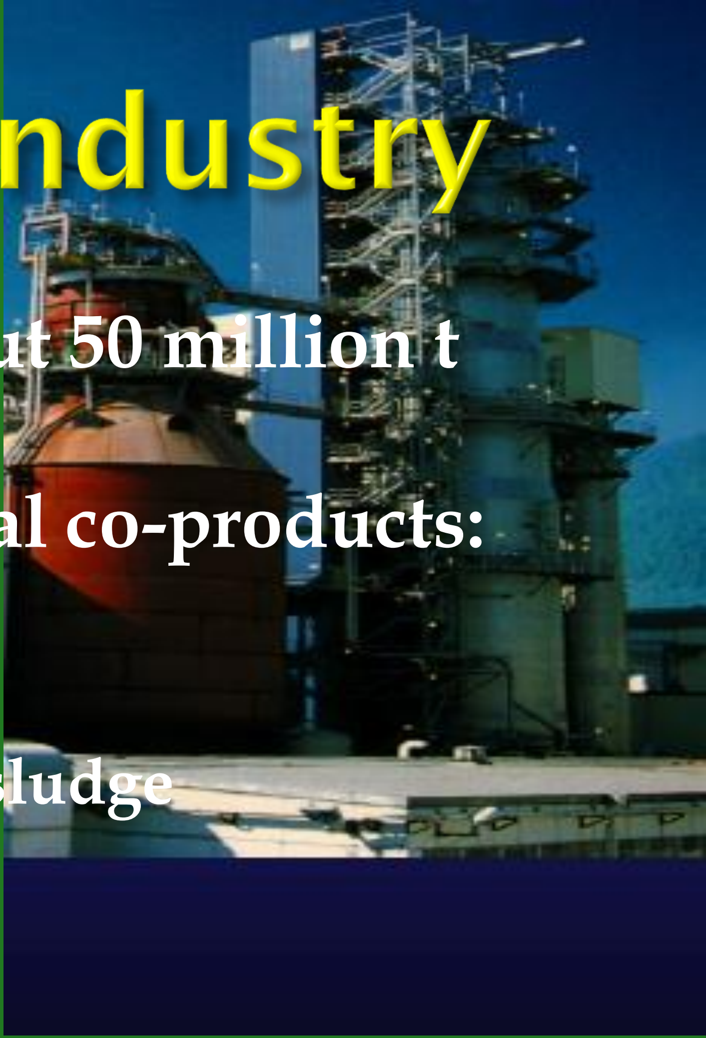
Lew P. Christopher

Lakehead UNIVERSITY | Biorefining Research Institute

Canadian Forest Industry

- Contributes roughly 12% ($58 billion) to Canada’s annual GDP
- One of Canada's largest employers, operating in 200 forest-dependent communities from coast to coast, and directly employing 235,000 Canadians across the country
- Canada is the world’s largest producer of newsprint and bleached softwood pulp
- Canada has the world’s largest supply of well-managed, high quality conifer wood fibre from the Boreal Forest

Canadian P&P Industry



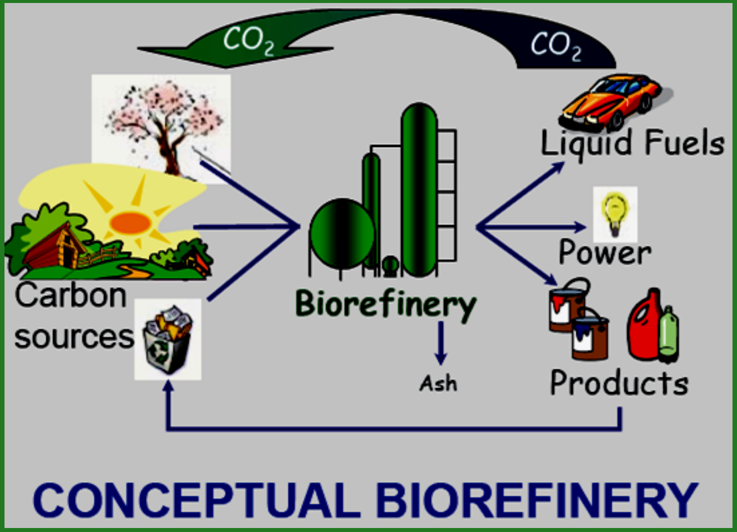
- Canadian P&PI processes about 50 million t pulpwood per annum
- Potential revenue from residual co-products:
  - 1 billion gallons ethanol
  - 300 million gallons acetic acid
  - 2.5 million t of paper mill waste sludge
    - low value as waste product
    - feedstock for ethanol
    - no pretreatment
  - 350 million liters of turpentine and tall oil
    - feedstock for biodiesel
  - $3 billion net cash flow

The Way Forward

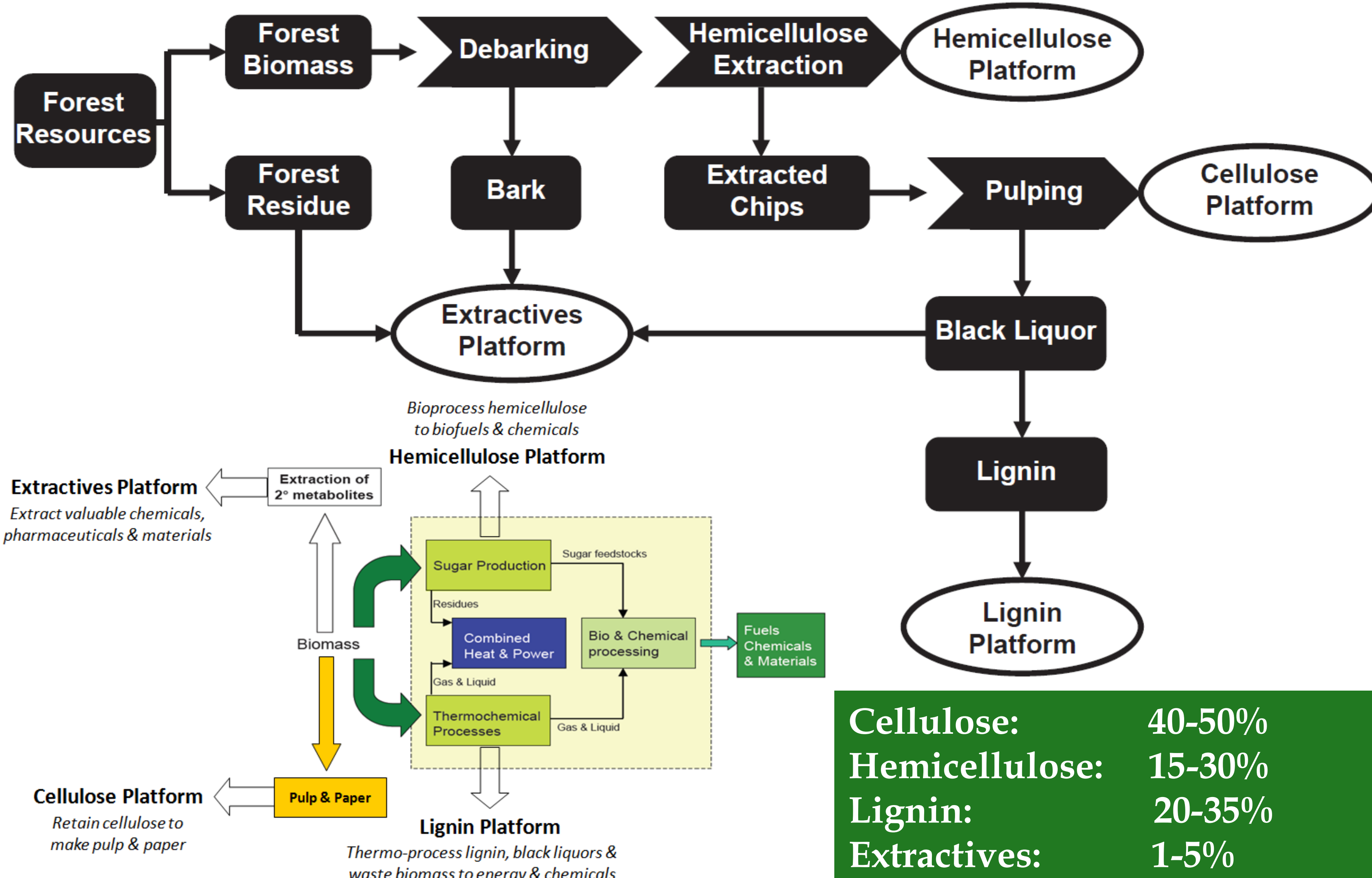
- Strong & increasing off-shore competition (new modern mills, fast growing trees, inexpensive labor)
- Unstable & fluctuating oil prices
- Uncertainties about oil reserves
- Greenhouse gas emissions
- Global movement & premium for green fuels and chemicals
- Need of a new business model and additional revenues to remain competitive
  - Diversify products
  - Diversify markets
- Need to convert to Integrated Forest Biorefineries (IFBRs)

Integrated Forest Biorefineries (IFBR)

A processing and conversion facility that fully integrates forest biomass and other biomass waste for simultaneous production of marketplace products, including fibers for pulp & paper, chemicals and energy

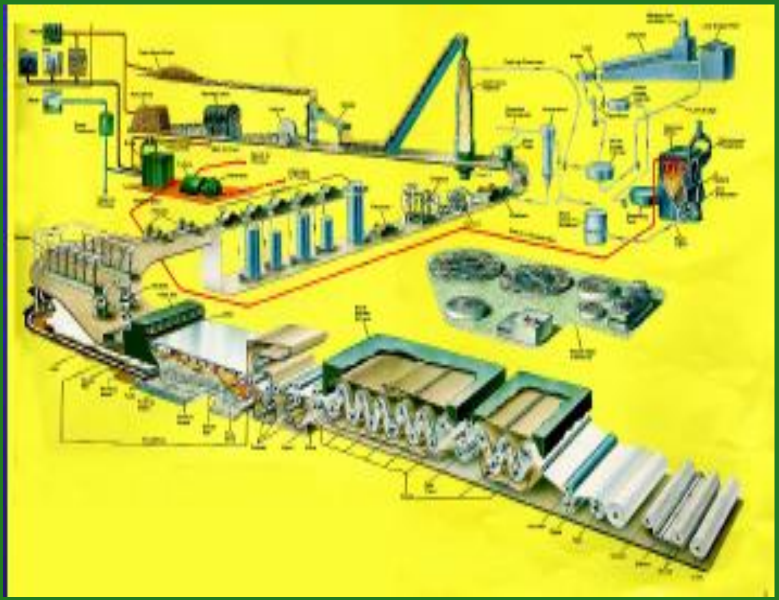


Biorefinery Concept and IFBR Platforms



Cellulose:	40-50%
Hemicellulose:	15-30%
Lignin:	20-35%
Extractives:	1-5%

Hemicellulose Platforms



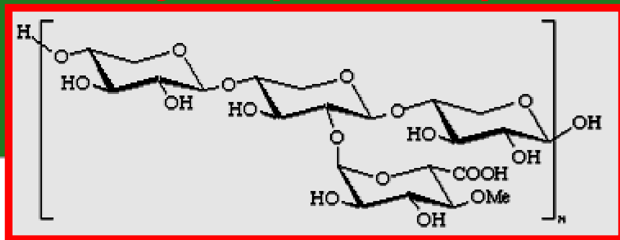
Hemicellulose - underutilized in current pulp & paper making process

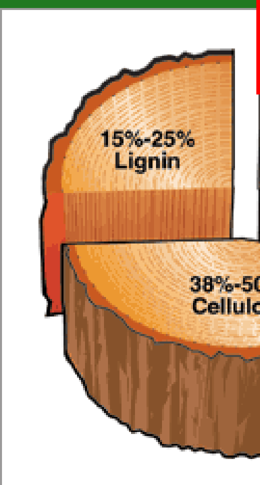
Hemicellulose - degraded during pulping: oligomers, monomers (xylose, mannose), furfural and HMF

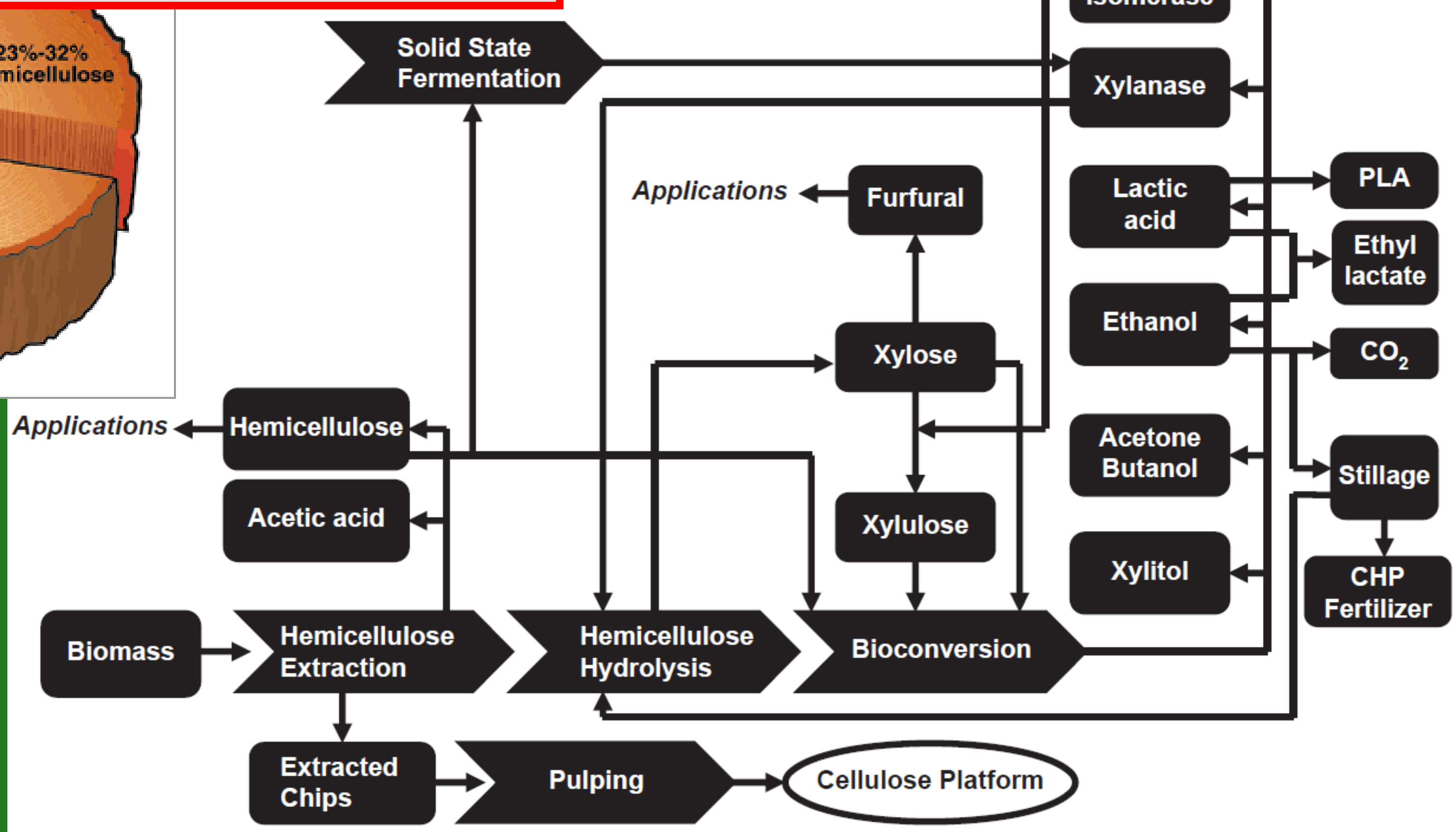
Low heating value of hemicellulose - about half (13.6 MJ/kg) that of lignin (27 MJ/kg) – 25% contribution to total heat in recovery boiler

Hemicellulose Platform

Xylan (DP ~ 200)







Xylan

Pharmaceutical Industry

Anticoagulant
Cholesterol-reducing
anti-cancer agent (PPS)
Anti-tumor drug (CMX)
Anti-inflammatory action
Wound treatment agent
Tabletting material
HIV-inhibitor
Dietary fiber

Xylan

Xylanase

Pulp and Paper

Beater additive
(improved swelling,
shorter beating times,
faster drainage,
higher porosity,
better strength at lower cost
Coating of fibers
Stabilizer of wood resin

Fermentation

Fermentation substrate for production of:

Enzymes:
xylanase, xylosidase,
xylose isomerase
Biopolymers: PHB
(polyethelene,polypropelene)

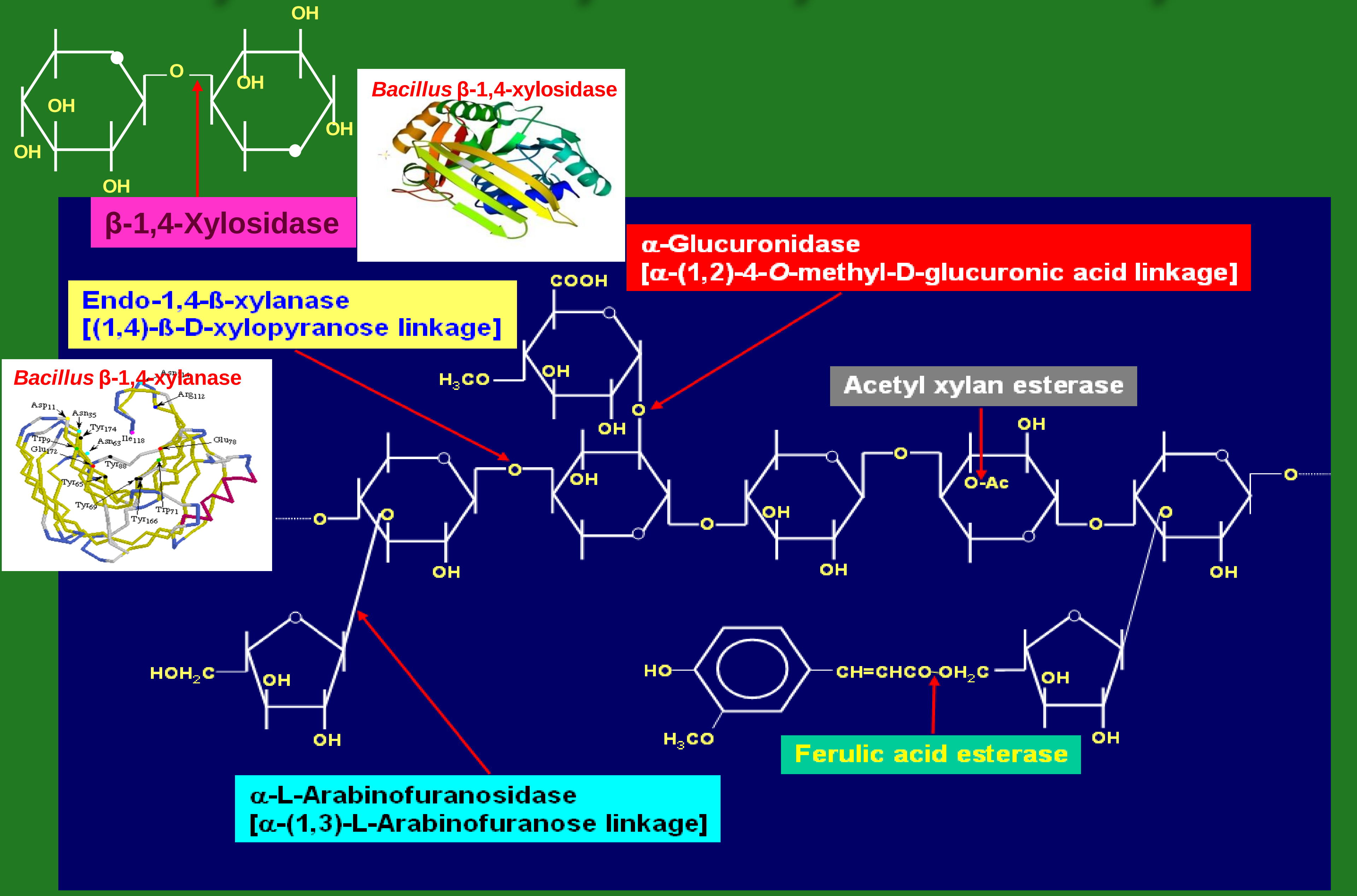
Chemical Industry

Thermoplastic material
(xylan carbamates,
hydroxypropyl xylan)
Filler for polypropylene
Gel forming material
Paint formulations
Xylan oligomers as chiral polymer building blocks

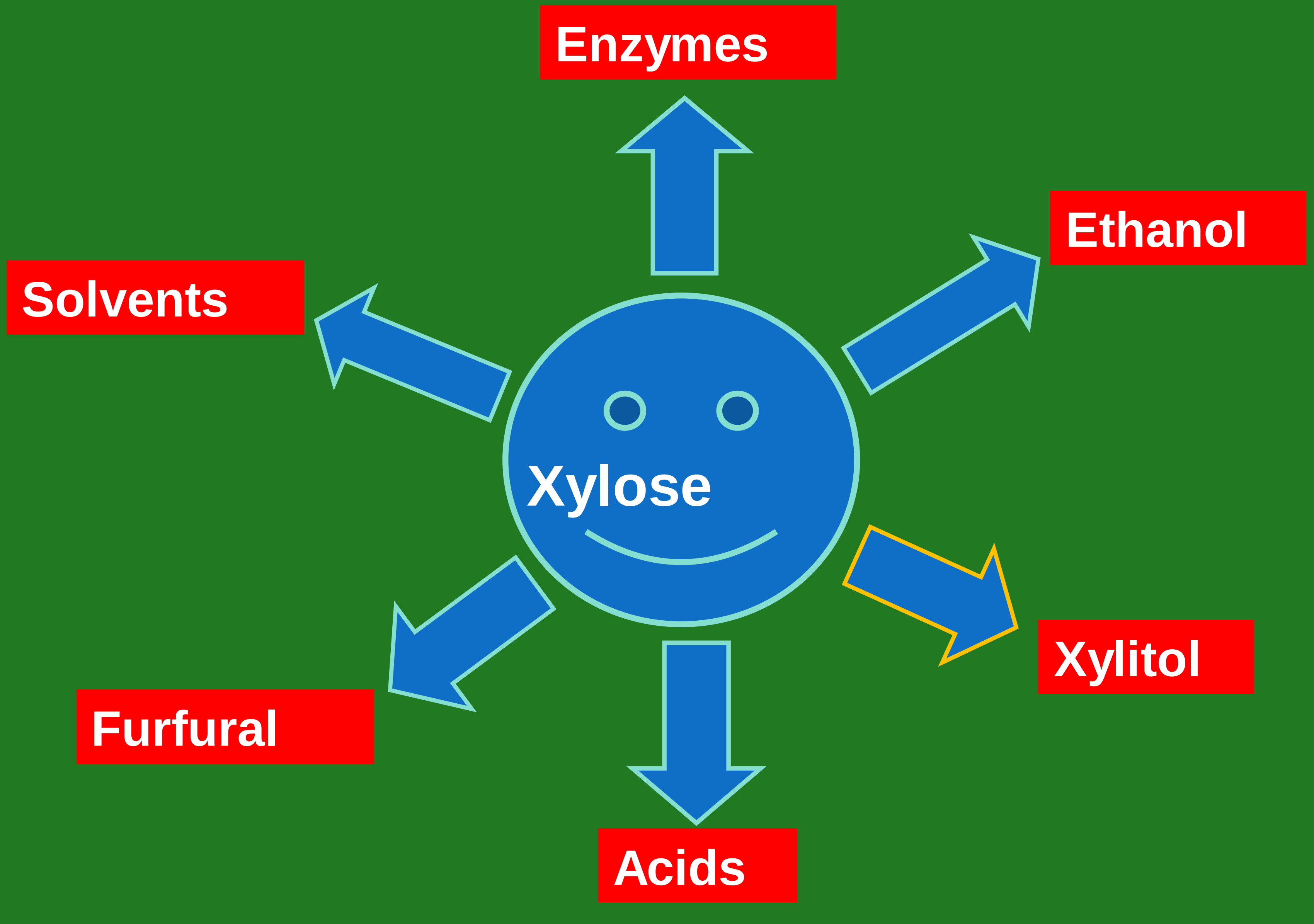
Food Industry

Xylose
Xylitol
Biodegradable polymers:
plastics, films, coatings
(acetyl xylans with
increased hydrophobicity
and water resistance)

Enzymatic Hydrolysis of Xylan

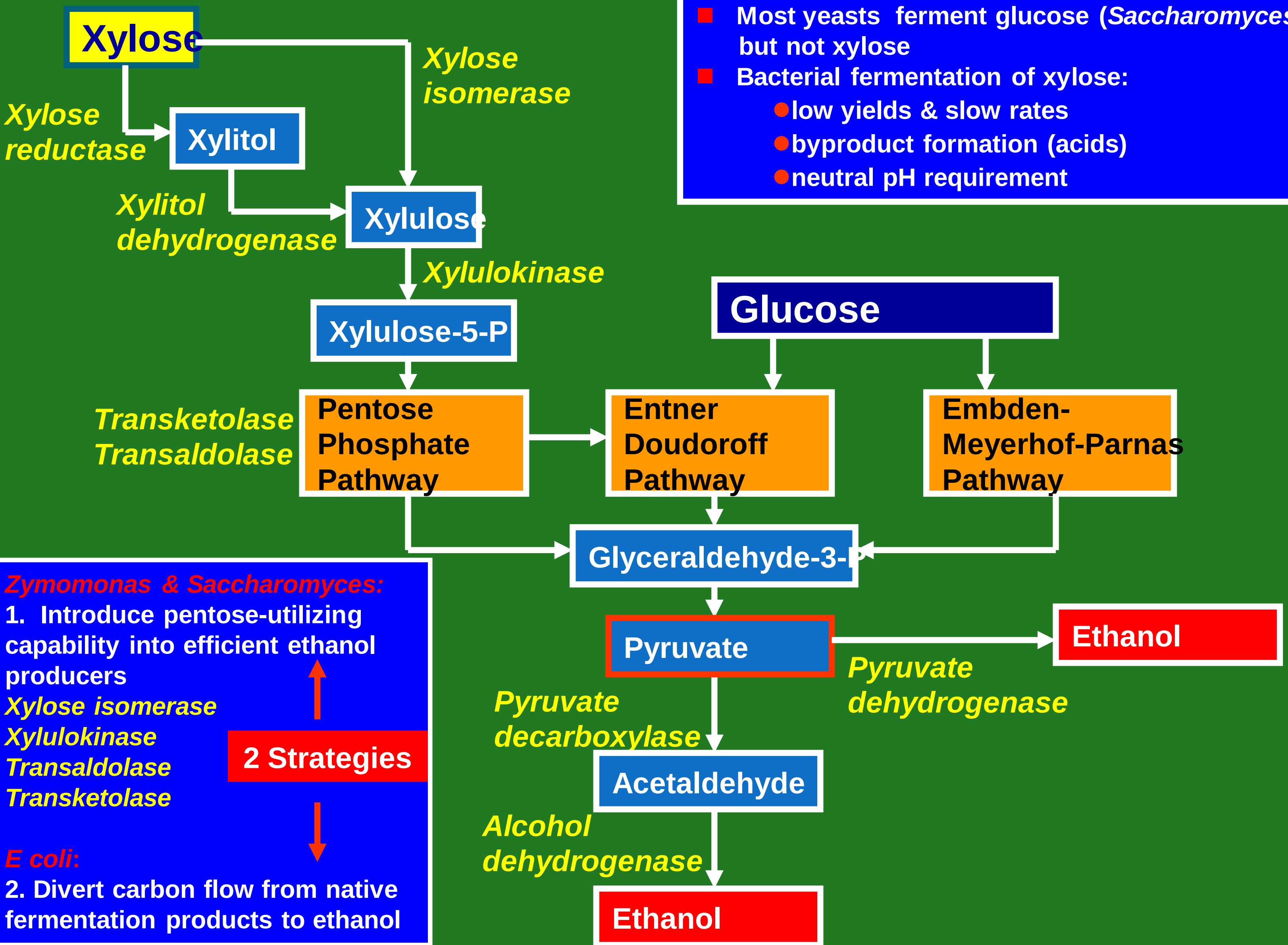


Xylose Applications



Xylose Fermentation to Ethanol

- Most yeasts ferment glucose (*Saccharomyces)* but not xylose
- Bacterial fermentation of xylose:
  - low yields & slow rates
  - byproduct formation (acids)
  - neutral pH requirement



Zymomonas & Saccharomyces:

1. Introduce pentose-utilizing capability into efficient ethanol producers

Xylose isomerase
Xylulokinase
Transaldolase
Transketolase

2 Strategies

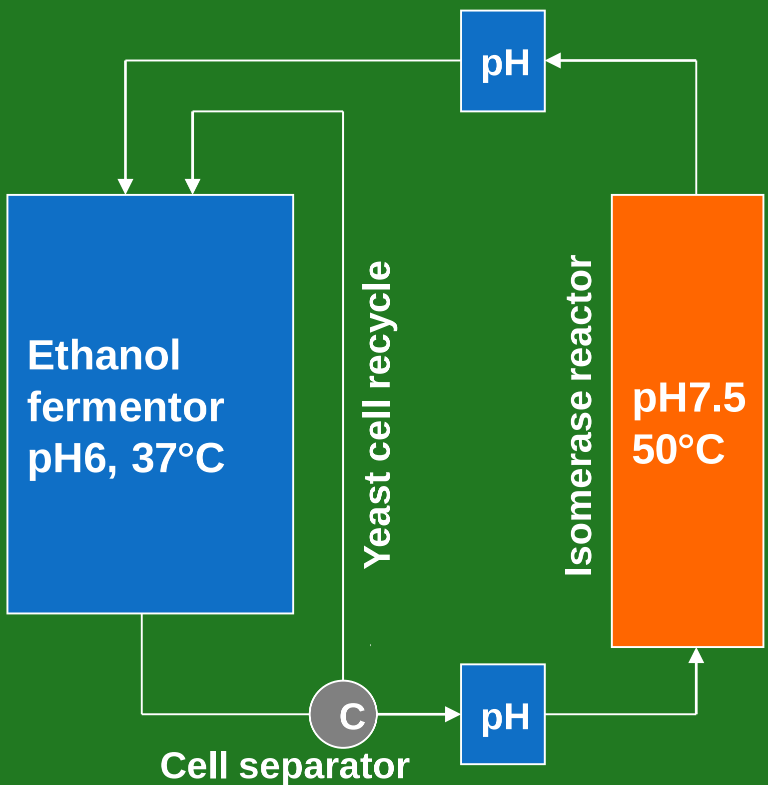
E coli:

2. Divert carbon flow from native fermentation products to ethanol

Xylose Isomeration-Fermentation to Ethanol

Xylose → (**Xylose Isomerase**) → **Xylulose** → **Pentose Phosphate Pathway** → **Glycolysis** → **Ethanol**

efficient ethanol producer



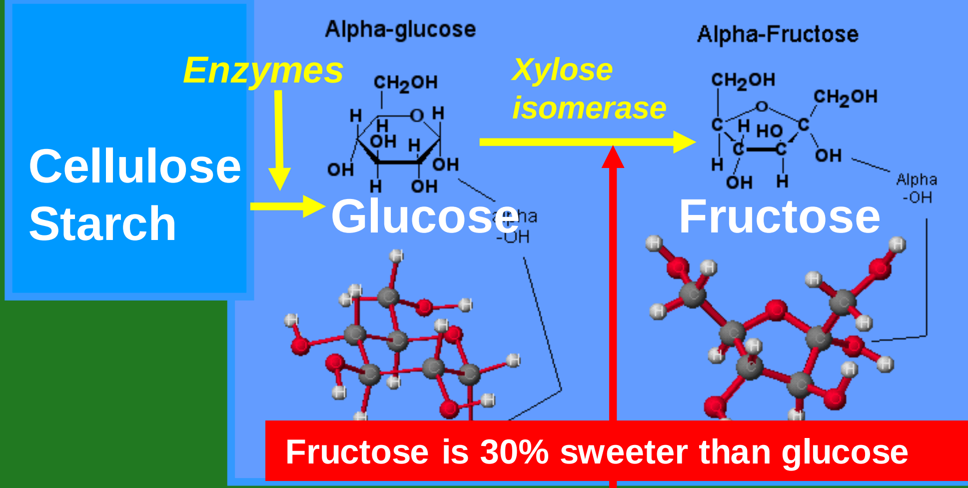
Best native ethanol producers on glucose: *Saccharomyces & Zymomonas*

Do not ferment xylose

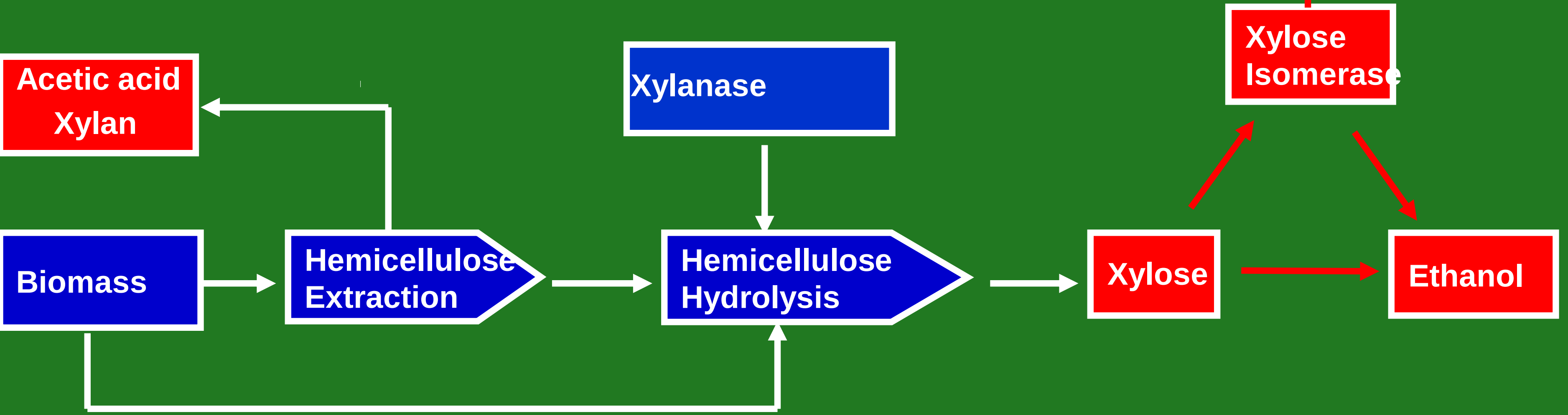
But can ferment xylulose

Use commercial xylose isomerase to convert xylose to xylulose

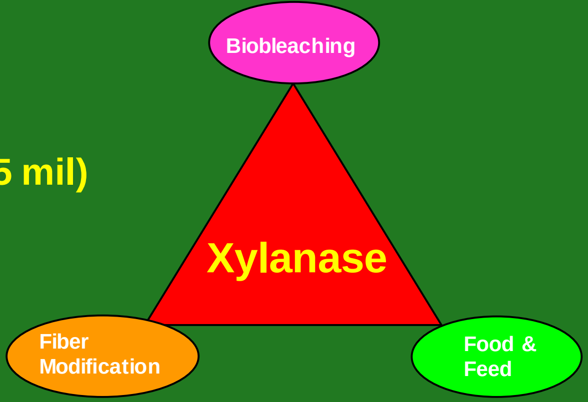
Xylose Isomerase



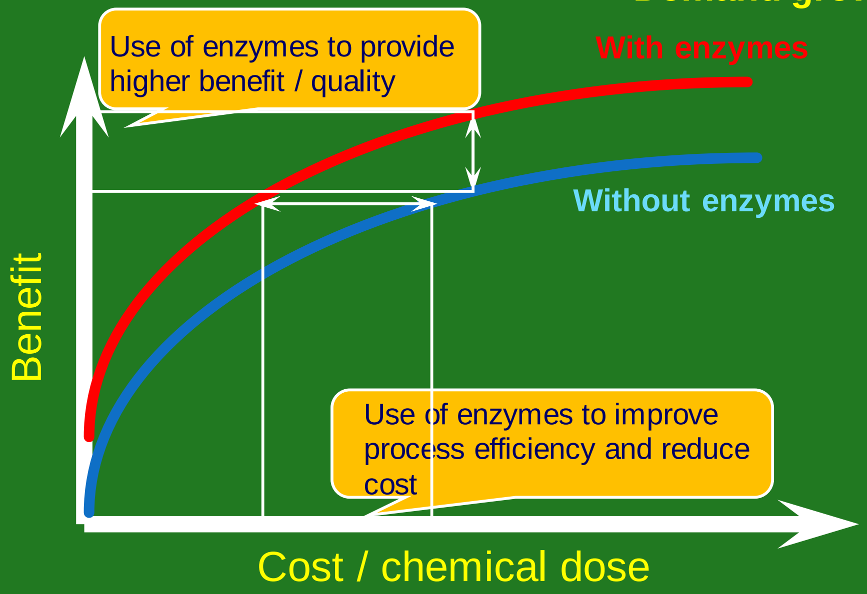
- World market for HFCS was 5 million tons in 2004
- HFCS currently dominate industrial sugar market in US

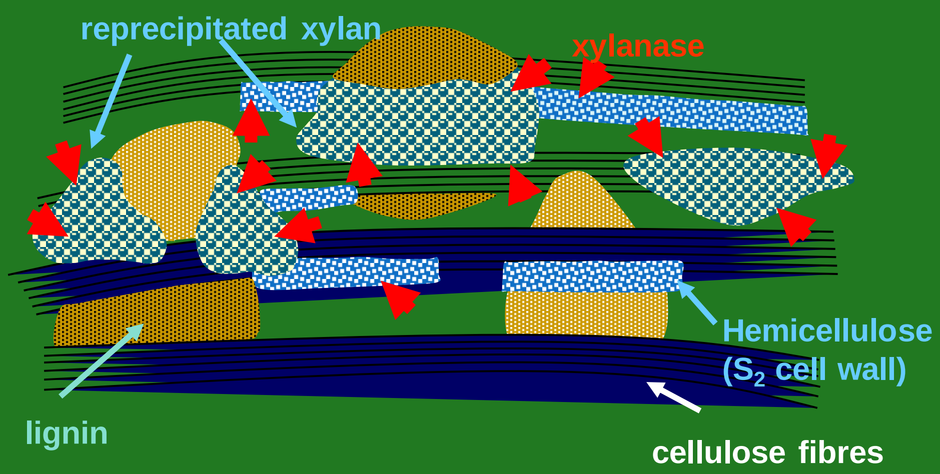


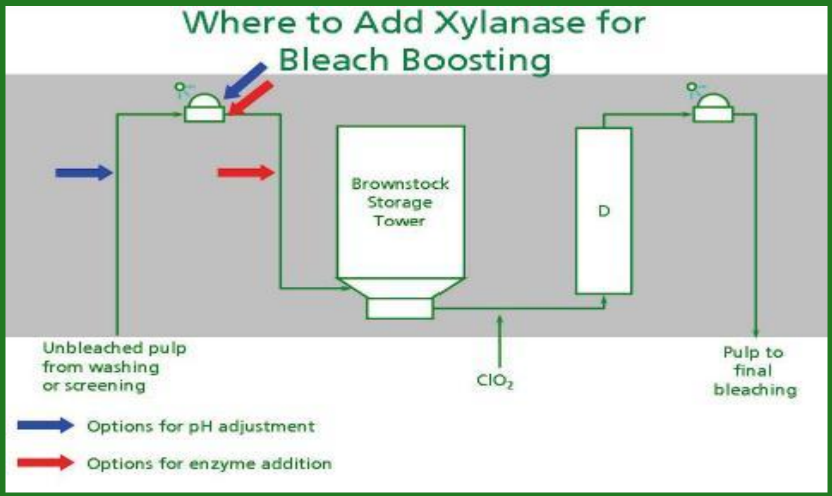
XYLANASE



50% of current world enzyme market ($15 mil)
Demand grows 25% pa







Benefits:

- Savings in bleach chemicals
- Increased pulp mill throughput
- Improved pulp properties (brightness)
- Preserved strength
- Savings in OBA
- Reduced AOX, chlorides, toxicity
- Positive environmental impact & public perception
- Marketing advantages

XYLITOL

Bioconversion

Atmospheric pressure
Low temperatures (30-35°C)
Less purification required
Higher conversion yields (65-90%)

Applications

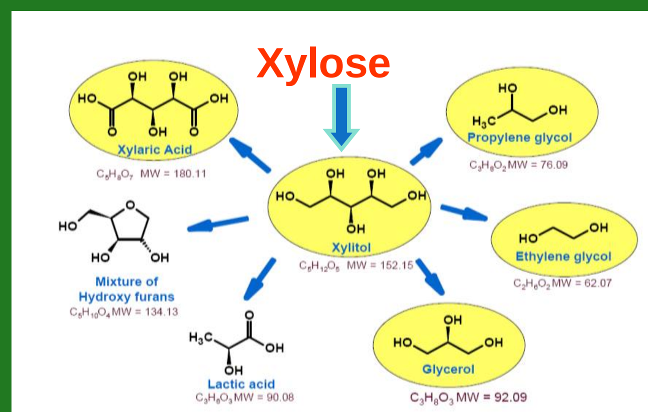
Anti-plaque action:
(for sugarless chewing gums & tooth paste world market: >12 million $)
Natural sweetener: Low glycemic index
Building block chemical: resins, antifreeze
Pharmaceuticals: Bone loss reverse - osteoporosis, prevents nose & ear infection

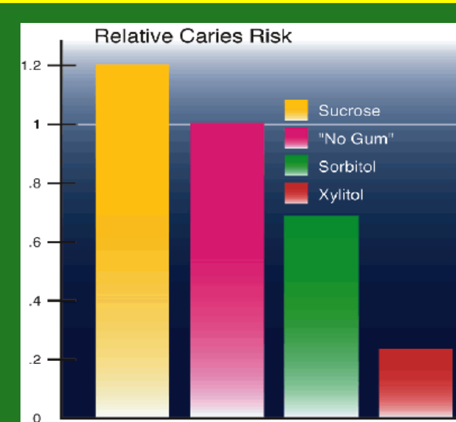
Chemical Catalysis

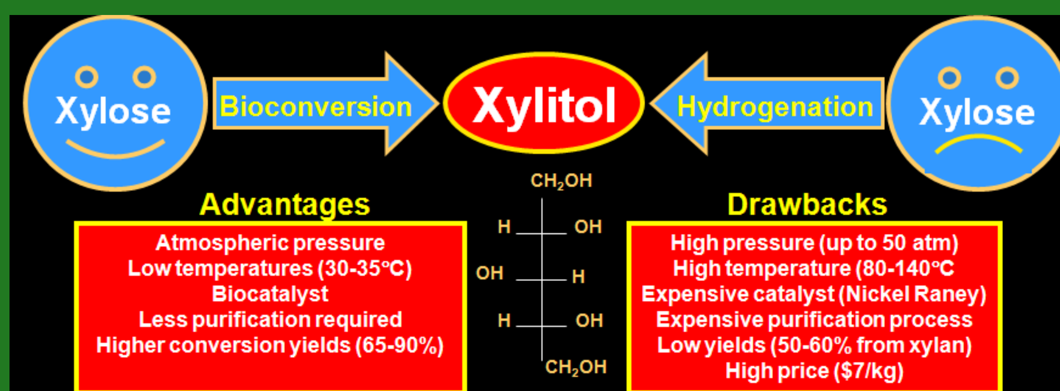
High pressure (up to 50 atm)
High temperature (80-140°C
Expensive catalyst (Nickel Raney)
Expensive purification process
Low yields (50-60% from xylan)

Natural fermenting yeasts
Candida tropicalis: yields 60-90%

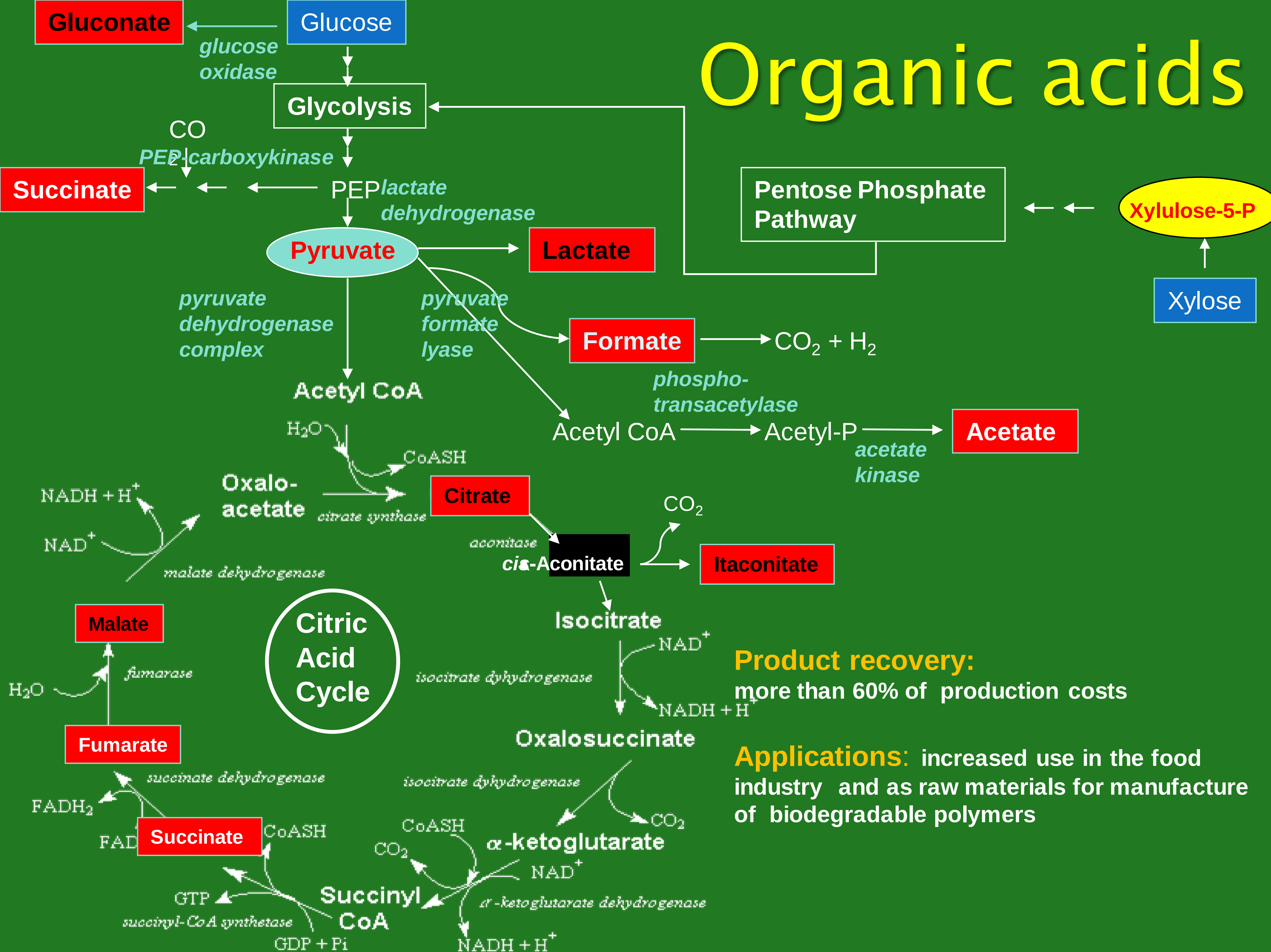
Recombinant yeasts
S. cerevisiae (with xylose reductase gene): 95% yield





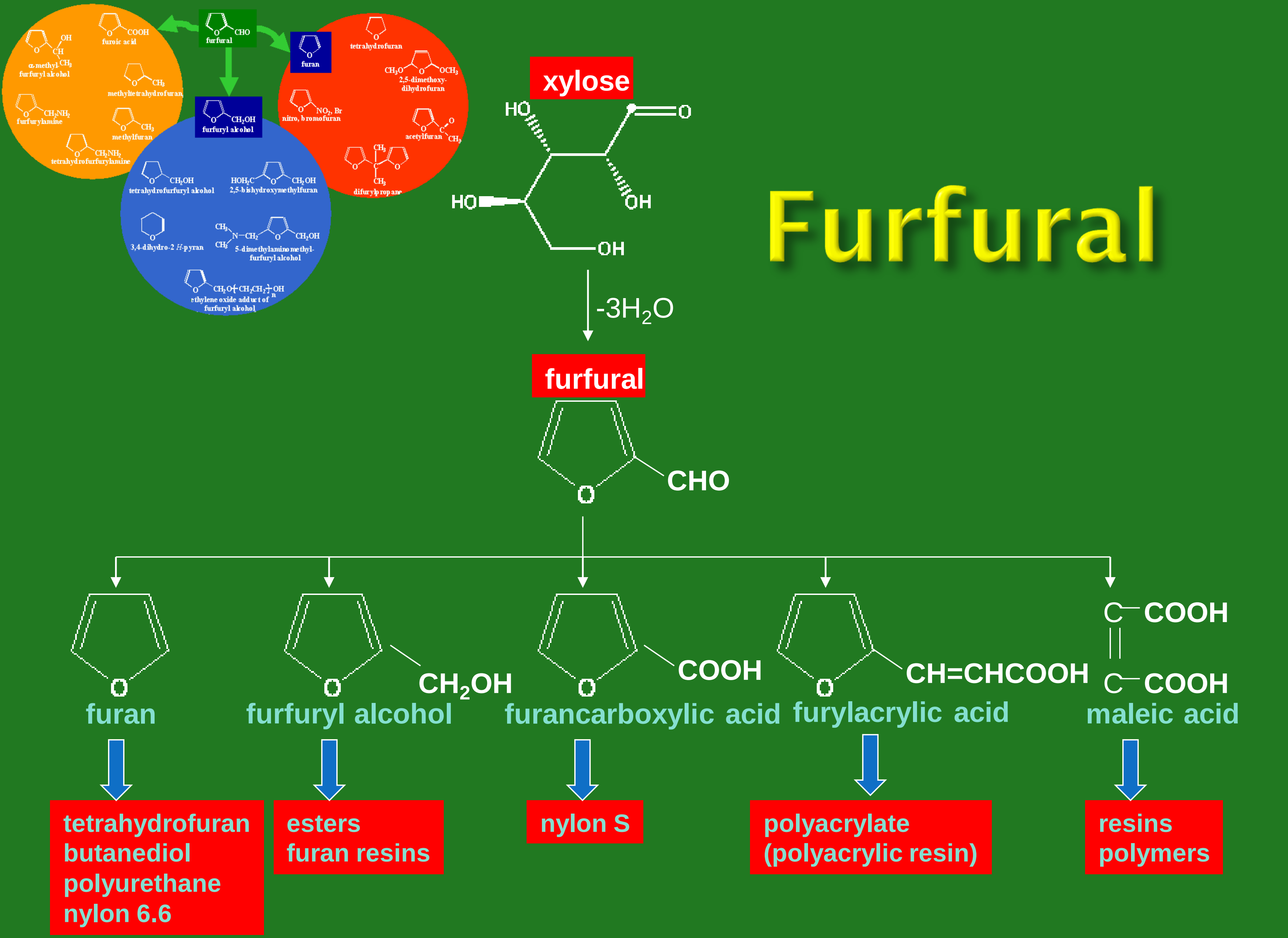


Organic acids



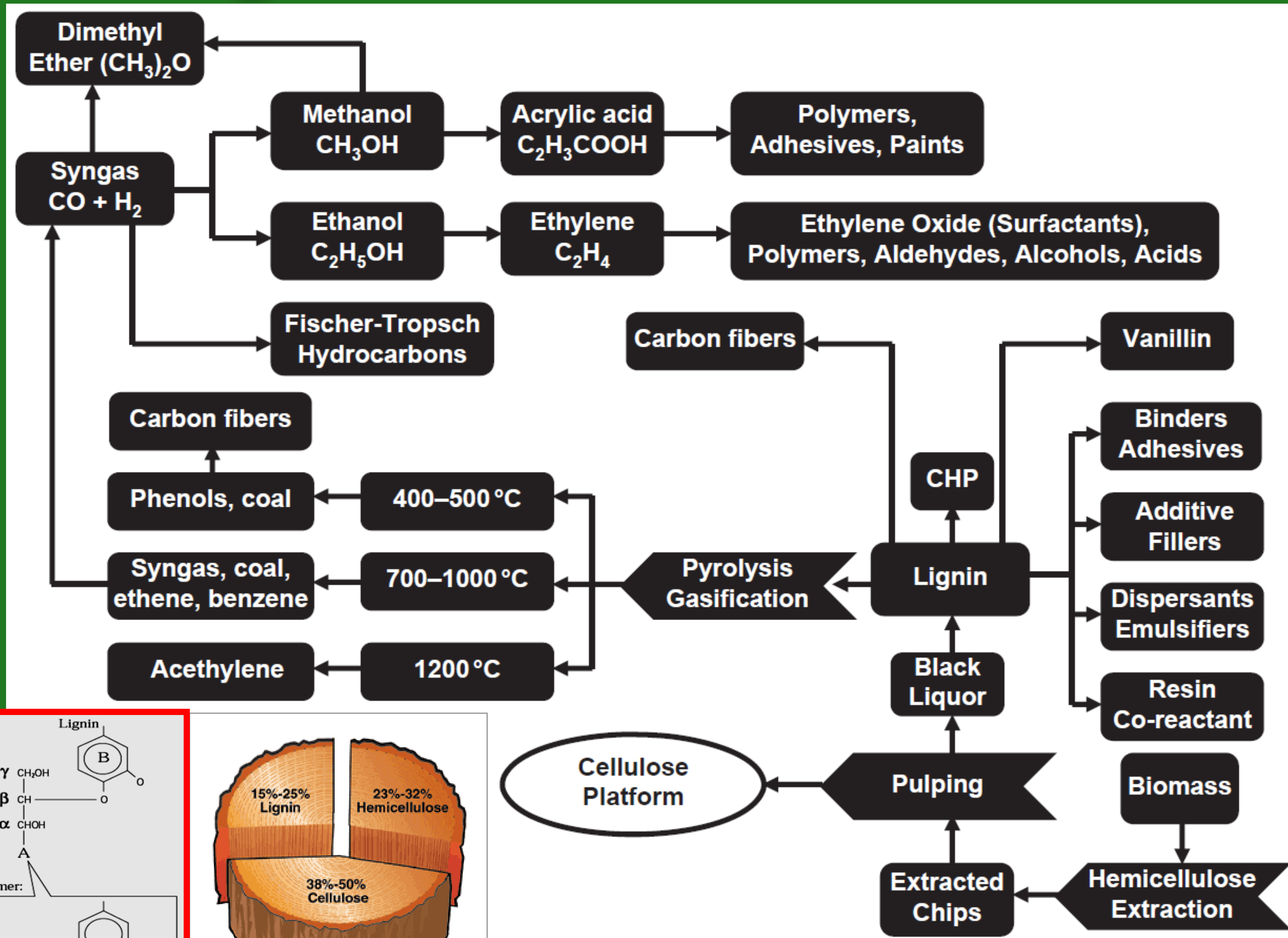
Product recovery: more than 60% of production costs

Applications: increased use in the food industry and as raw materials for manufacture of biodegradable polymers

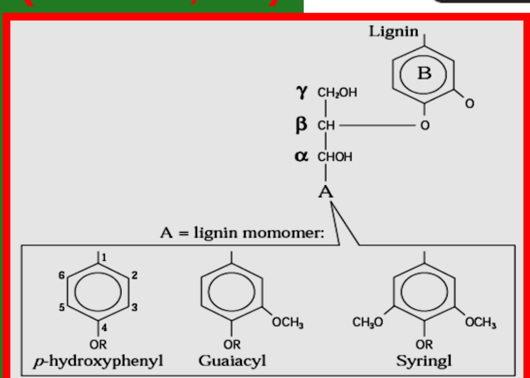


Furfural
xylose
HO
O
HO
OH
OH
-3H2O
furfural
CHO
O
furan
furfuryl alcohol
CH2OH
COOH
furancarboxylic acid
CH=CHCOOH
furylacrylic acid
C COOH
C COOH
maleic acid
tetrahydrofuran
butanediol
polyurethane
nylon 6.6
esters
furan resins
nylon S
polyacrylate
(polyacrylic resin)
resins
polymers
furfural
furoic acid
α-methyl furfuryl alcohol
methyltetrahydrofuran
furfurylamine
methylfuran
tetrahydrofurfurylamine
furfuryl alcohol
furan
tetrahydrofuran
2,5-dimethoxy-dihydrofuran
nitro, bromofuran
acetylfuran
difurylpropane
tetrahydrofurfuryl alcohol
2,5-bishydroxymethylfuran
3,4-dihydro-2 H-pyran
5-dimethylaminomethyl-furfuryl alcohol
ethylene oxide adduct of furfuryl alcohol

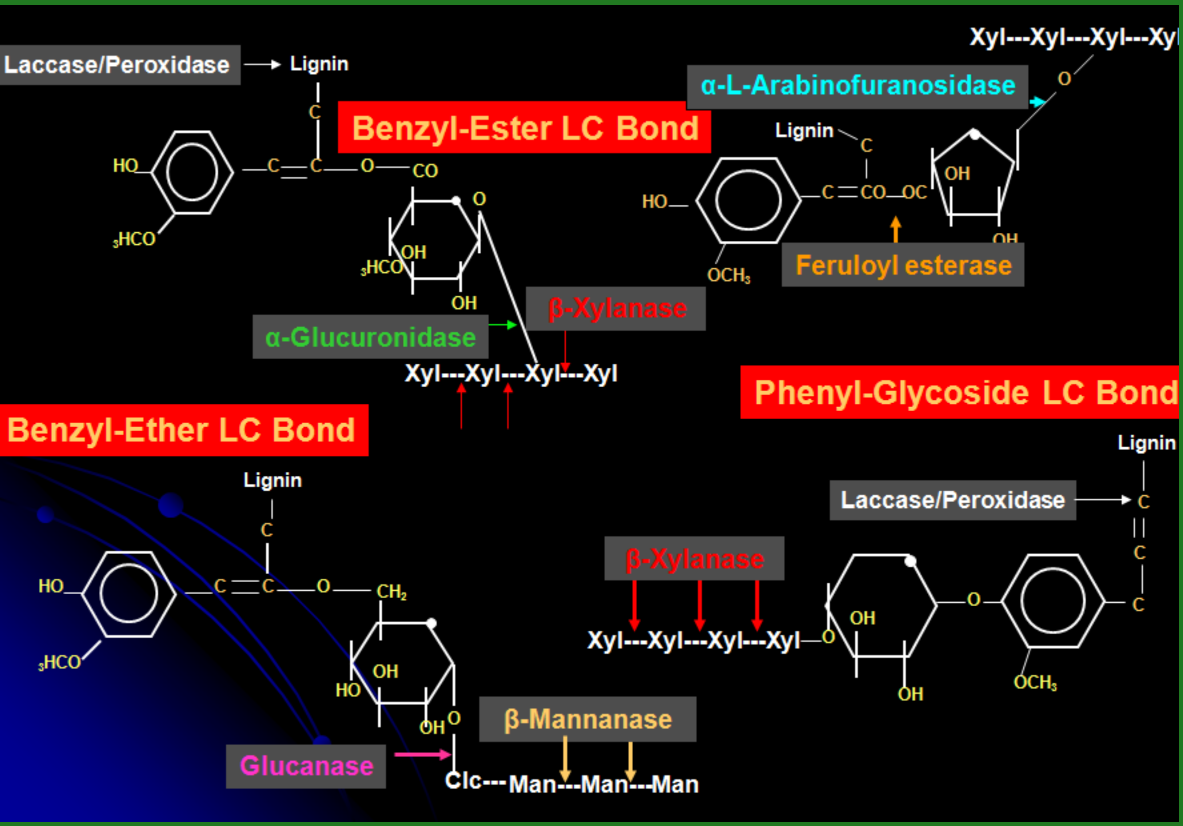
Lignin Platform



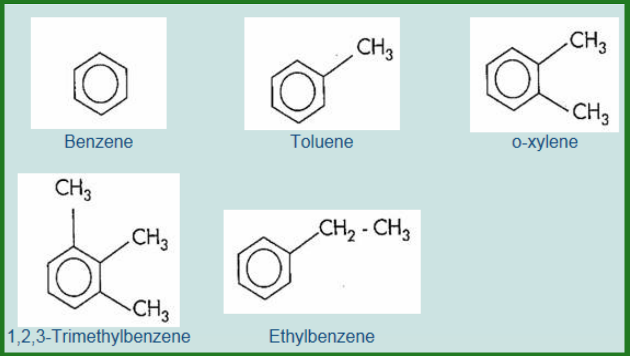
Lignin
(DP ~ 20,000)

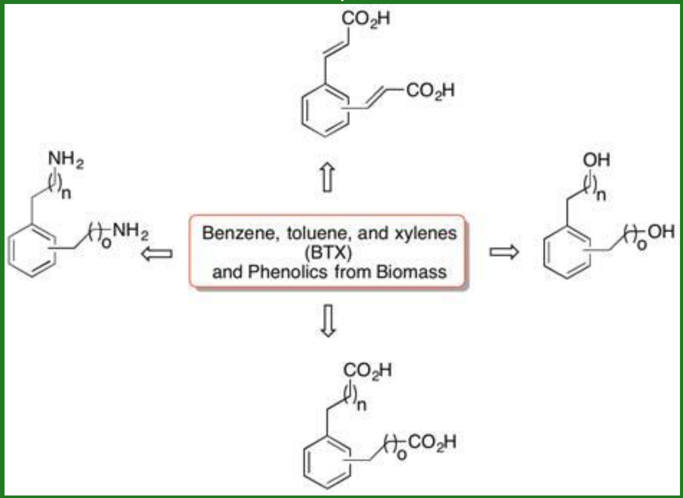


Lignin Breakdown to BTEX

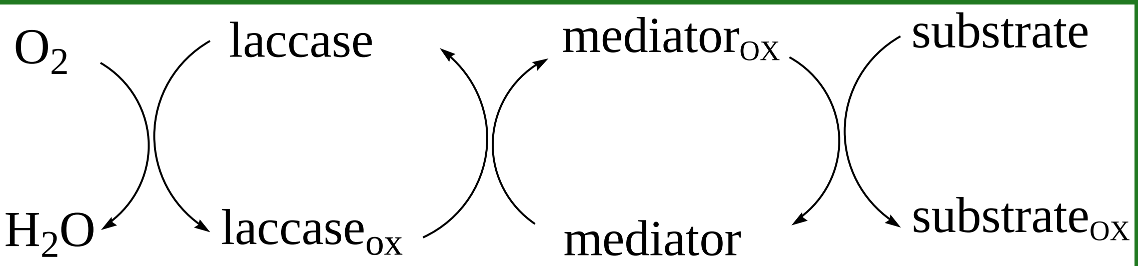


BTEX





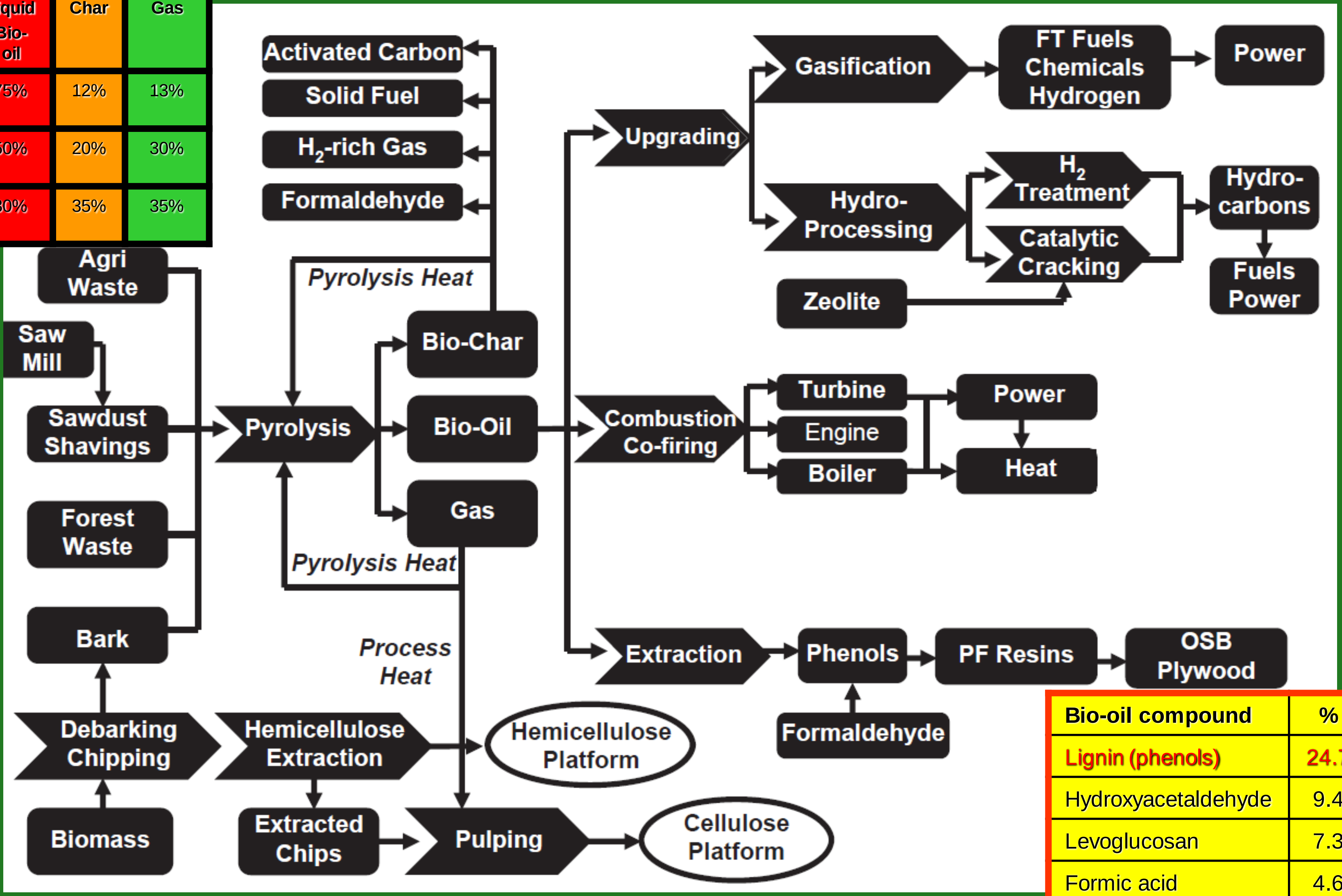
Conversion of BTEX to monomers for preparation of polyamides, polyesters, polyurethanes



Lignin degradation by Laccase-Mediator Systems

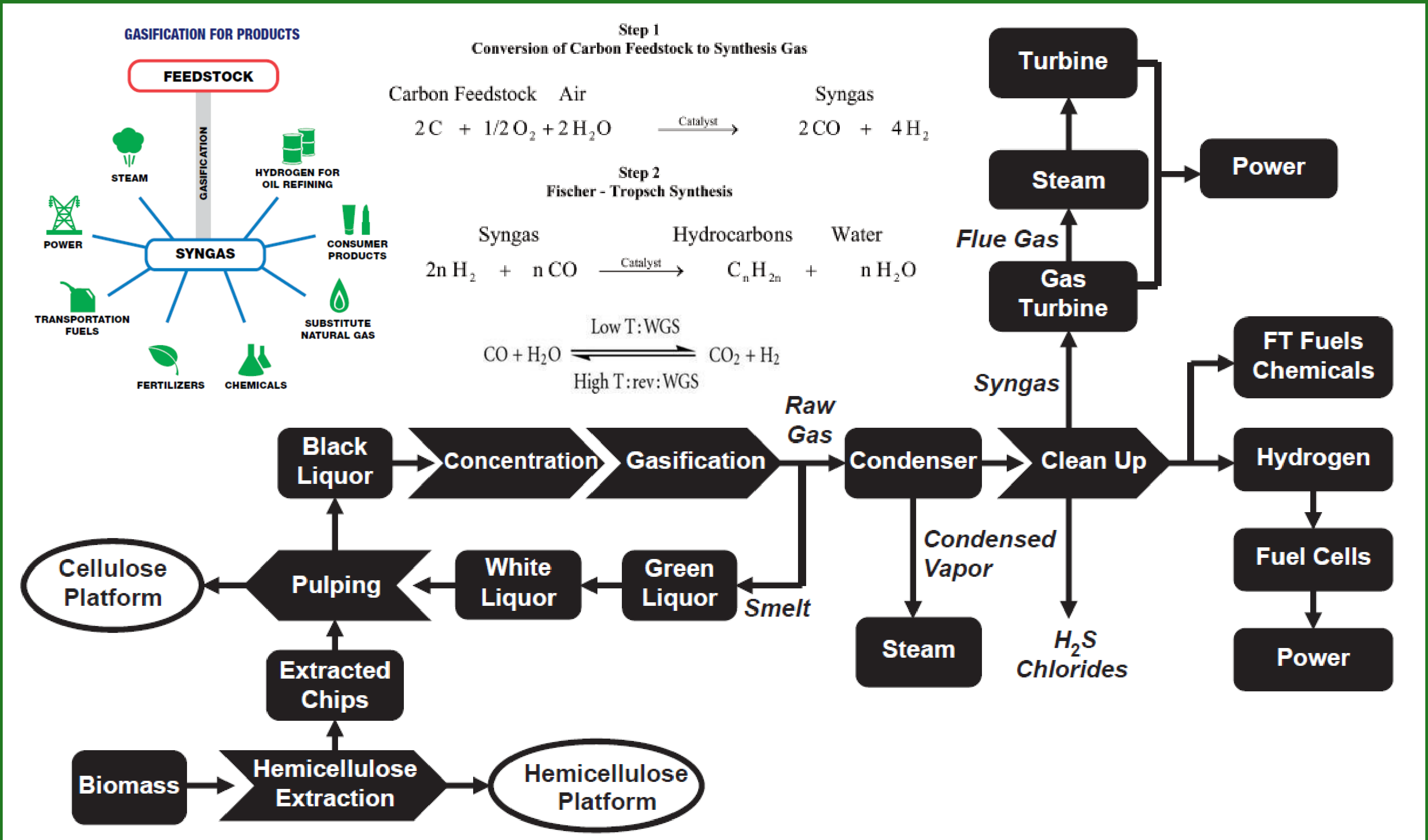
Lignin/Biomass Pyrolysis

Mode	Temp & Time	Liquid Bio-oil	Char	Gas
Fast	500°C; 1-2 s	75%	12%	13%
Med	500°C; 10-20 s	50%	20%	30%
Slow	400°C; long RT	30%	35%	35%

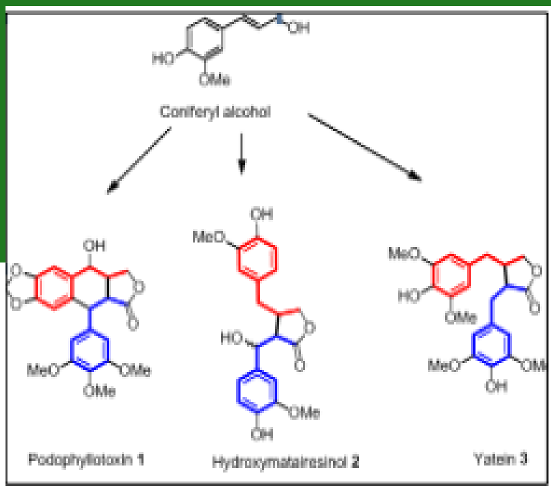


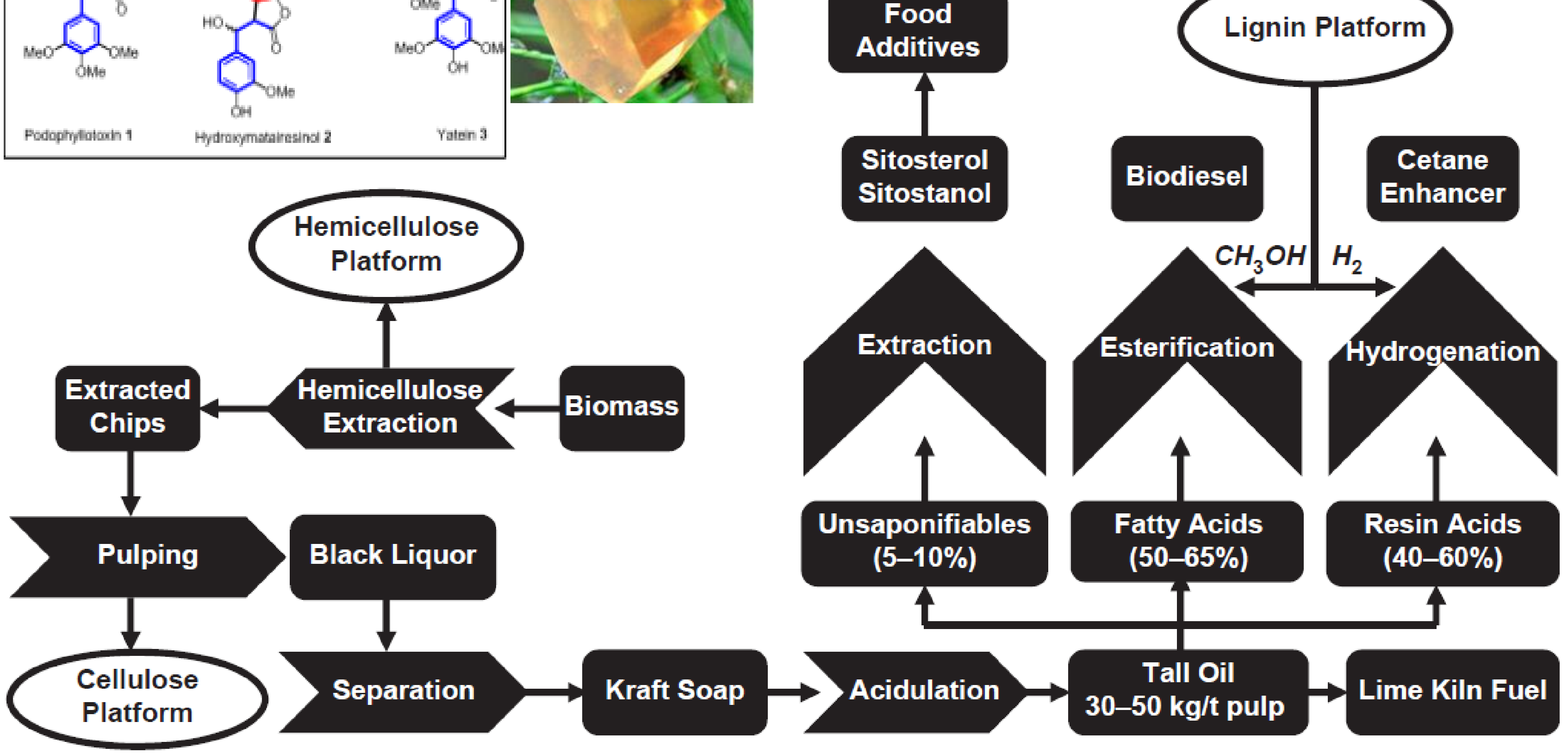
Bio-oil compound	%
Lignin (phenols)	24.7
Hydroxyacetaldehyde	9.4
Levoglucosan	7.3
Formic acid	4.6
Acetic acid	4.5
Formaldehyde	3.4

Black Liquor Gasification

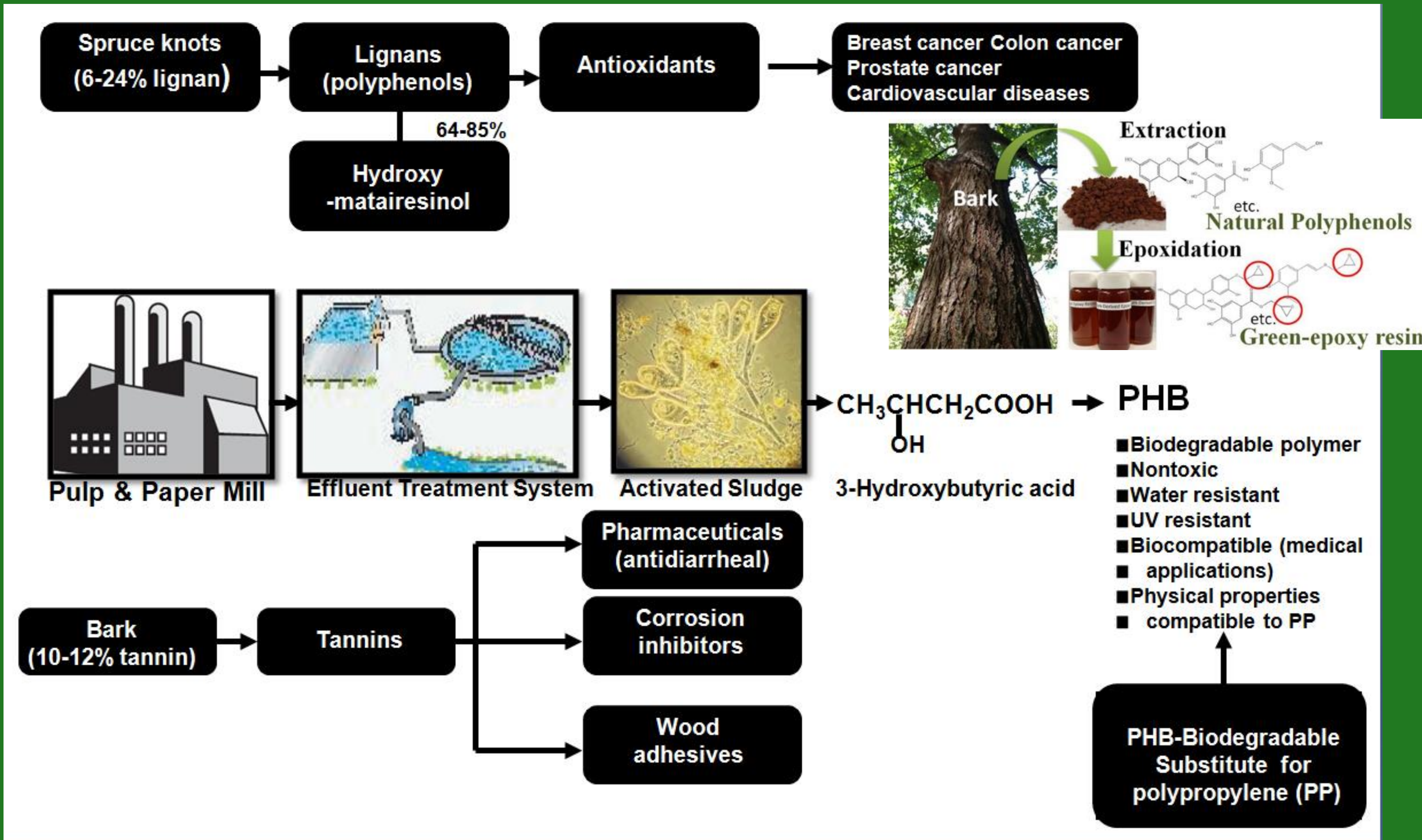


Extractives Platform

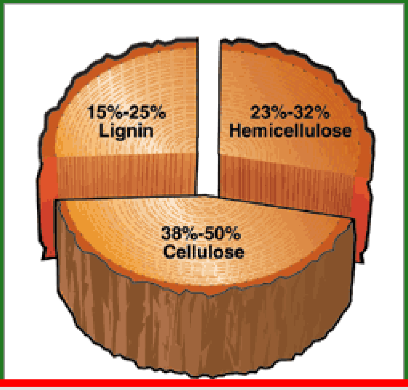


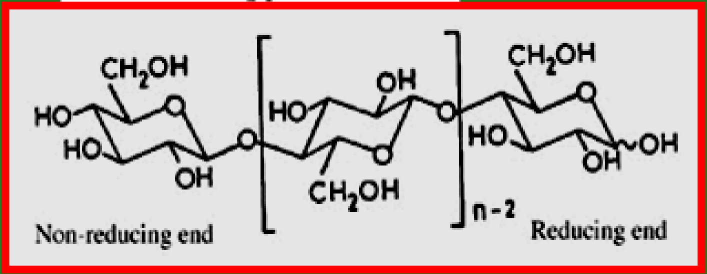


Extractives Platform



Cellulose Platform

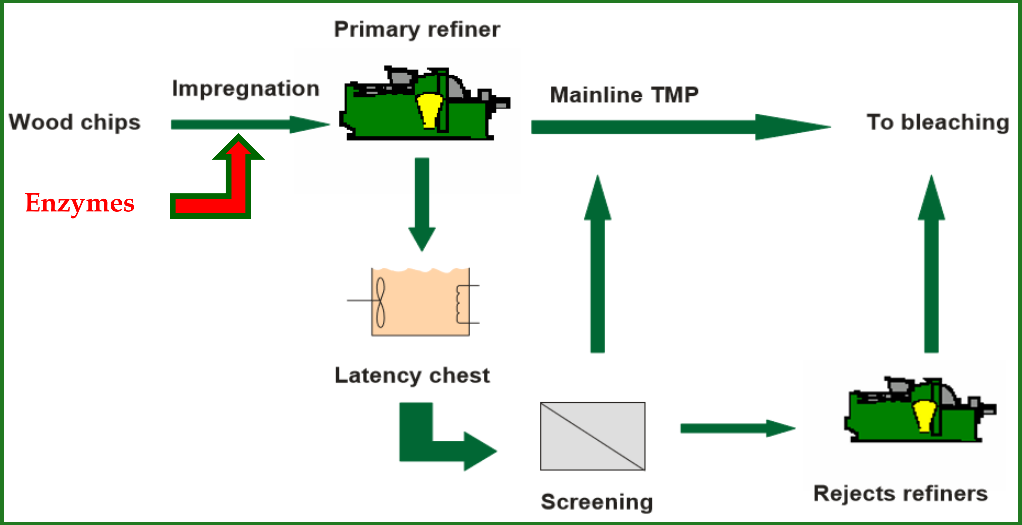




Cellulose (DP ~ 10,000)

Enzymes	Application in Pulp & Paper Manufacture
Xylanase	Bleach boosting, Refining energy reduction
Lipase	Pitch control, Clean-up
Cellulase	Deinking, Refining energy reduction, Tissue softness, Drainage
Laccase	Fibreboard bonding, Delignification
Pectinase	Refining energy reduction, Anionic trash removal
Amylase	Drainage improvement (OCC), Deinking, Starch modification
Protease	Clean-up, Slime control
Catalase	Corrosion inhibition, Peroxide removal
Oxalate decarboxylase	Descaling

Enzymatic Refining of TMP (Biorefining)



TMP refining – energy-intensive process (2-3 MW/h/t TMP pulp) with over 60% of refining energy consumed for fibre separation

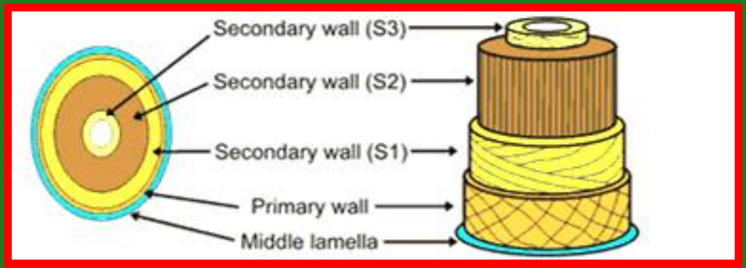
Fibre cell wall swelling and disruption prior to mechanical refining enhances fibre separation which leads to energy savings

Enzymes can:

- Swell & elongate cell wall
- Disrupt H-bonds in cell wall
- Reduce cellulose crystallinity
- Loosen internal cohesion in primary & secondary cell walls
- Degrade pectins & lignins in middle lamella

Benefits:

- Reduced refining energy at a given freeness and strength (10-30%)
- Improved strength properties at a given energy input (20%)



Enzymatic Improvement of Pulp Drainage

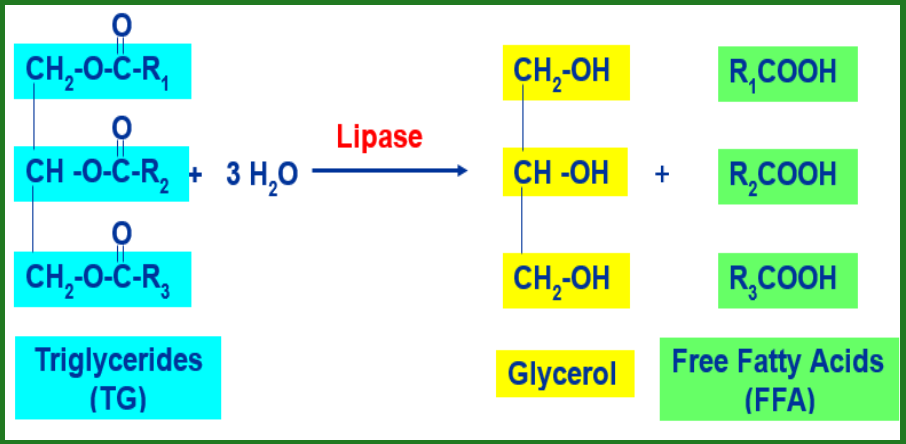
Enzymes can:

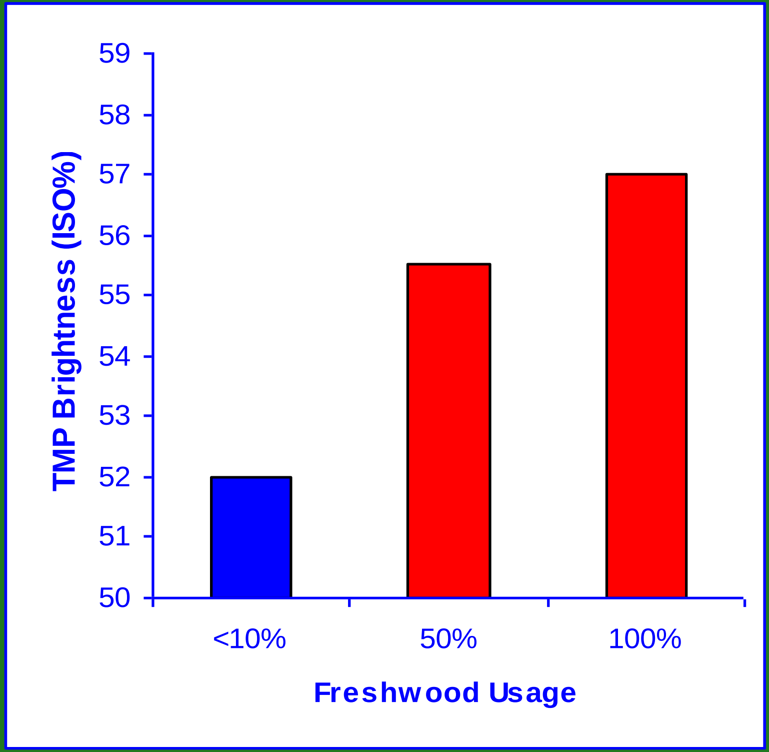
- Remove fines to improve drainage of secondary fibres
- Degrade starch in recycled OCC to improve drainage

Benefits from improved drainage:

- Increased PM speed and productivity
- Increased strength properties (tensile)
- Increased sheet density following PFI refining
- Reduced hornification of recycled fibres

Enzymatic Pitch Control





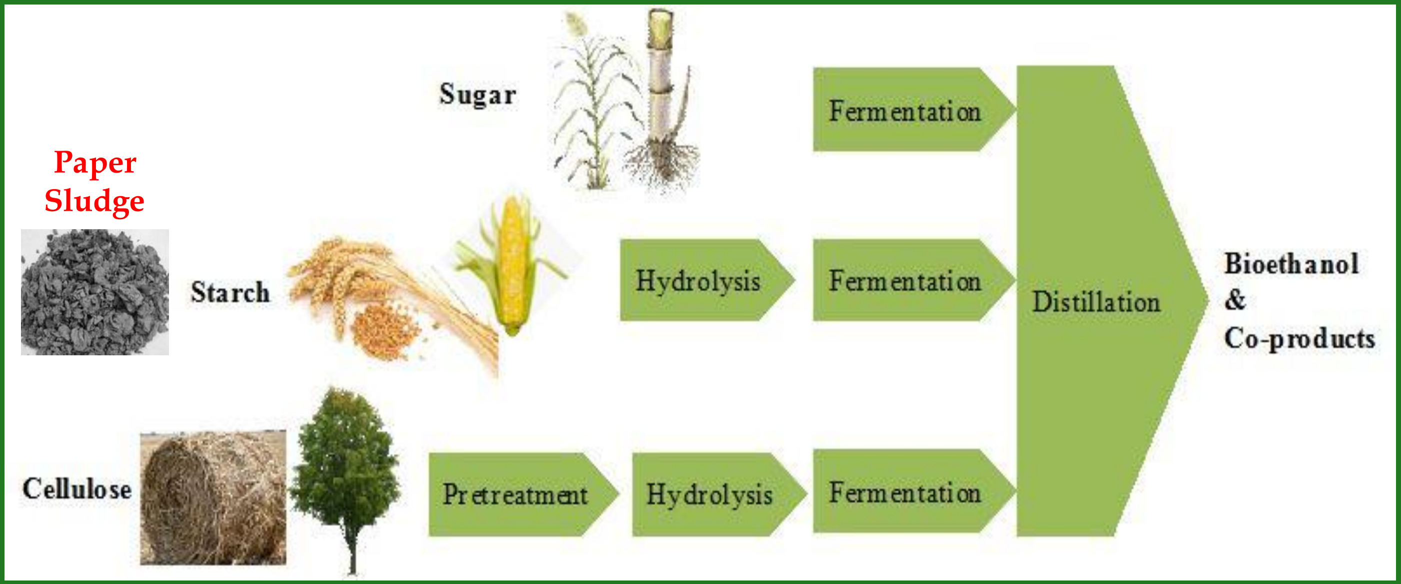
Benefits:

- Pitch & stickies removal
- Less down-time
- Improved PM speed
- Improved paper quality
  - Less deposits
  - Higher strength
- Increased wear life of forming and press fabric
- Possible use of more unseasoned wood
- Can be used on chemical and TMP pulps

Ethanol from Paper Sludge

Paper sludge:

- The largest solid waste stream produced by the pulp and paper industry
- Short fibre (fines) lost in paper production from recycled paper that cannot be retained on PM (15-20% of total)
- Disposed of in landfills as waste with no economic value
- Contains ~50 % carbohydrates; no pretreatment required
- Commercially-attractive, inexpensive feedstock for EtOH production
- Sludge-based EtOH is cost-competitive to corn-based EtOH
- Advantages: 1) use of non-food feedstock; 2) environmental benefits



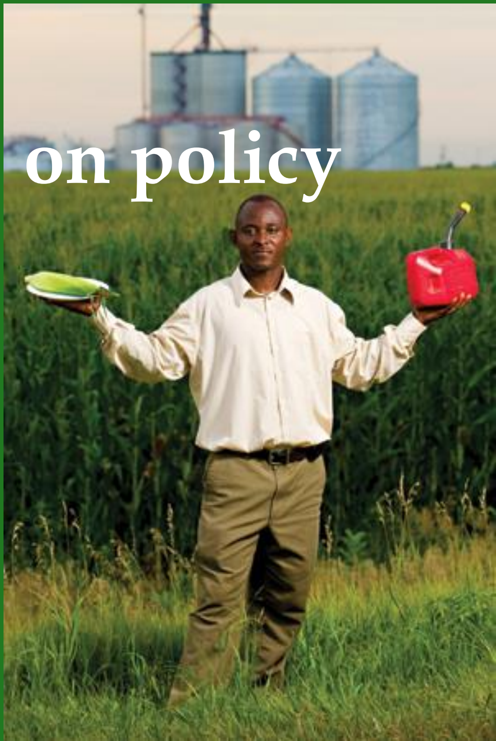
IFBR Technological Challenges

- **Optimize process conditions to maximize IFBR value:**
  - **Improve extraction & bioconversion efficiency of hemicellulose**
  - **Reduce costs for enzymatic processing**
  - **Remove remaining barriers to pyrolysis & gasification**
  - **Develop biomass-derived fuels and chemicals with novel functionalities as a cost-efficient alternative to oil-based fuels and petrochemicals**

- **Increase process integration to:**
  - **Reduce number of process steps**
  - **Reduce energy demand**
  - **Re-use process streams**

IFBR Socio-Economic Challenges

- Complex international systems of policies and regulations
- Concerns about environmental impact of biomass removal (deforestation)
- Pressure from environmental groups on policy makers
- Unstable commodity prices
- "Food vs Fuel" debate



Thank you