Development of a Bio-Based Process for Isoprene

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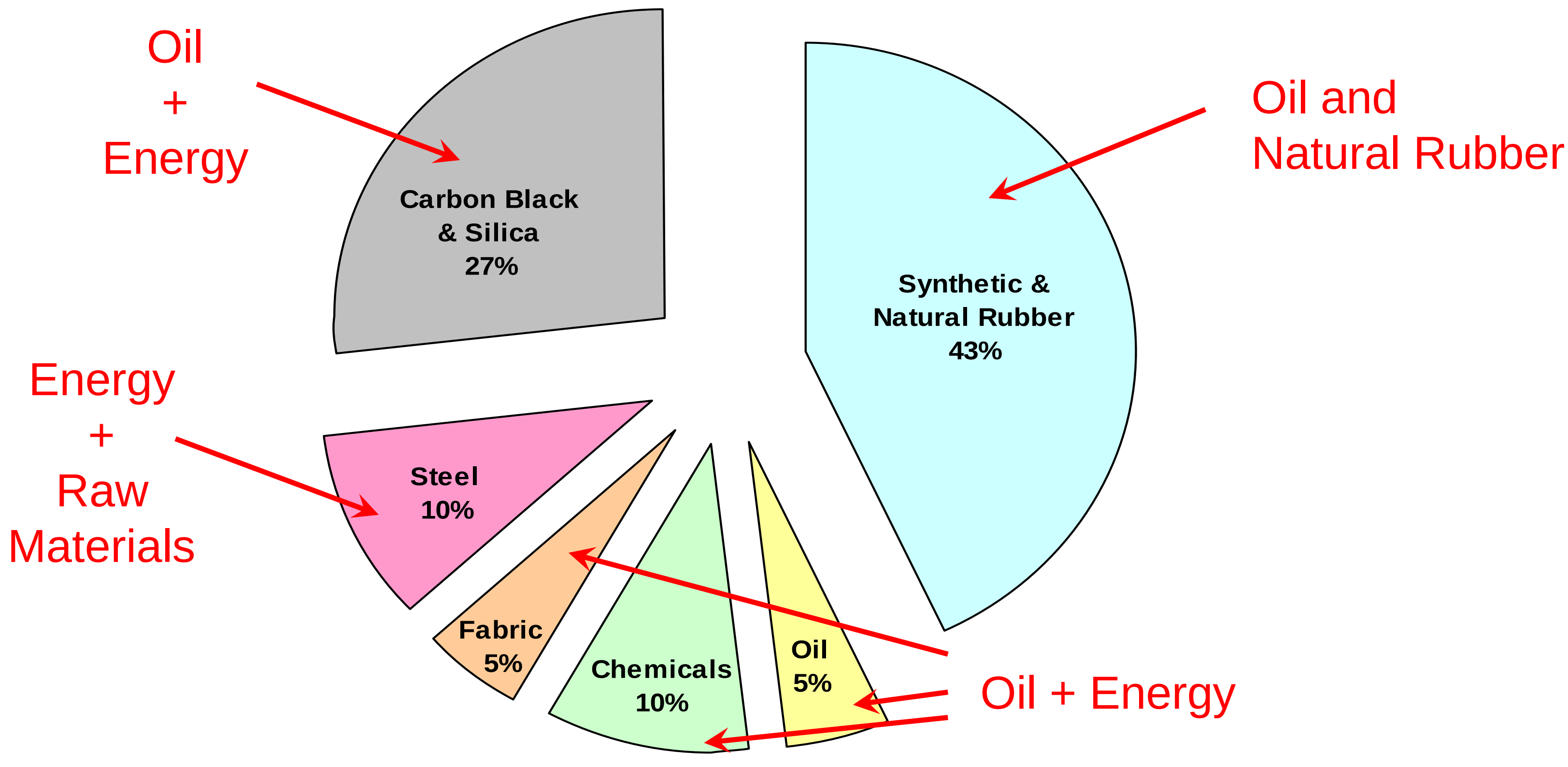
Typical Passenger Tire Composition



Over 70% petroleum derived

Natural Rubber (NR) is a Key Resource for Tires

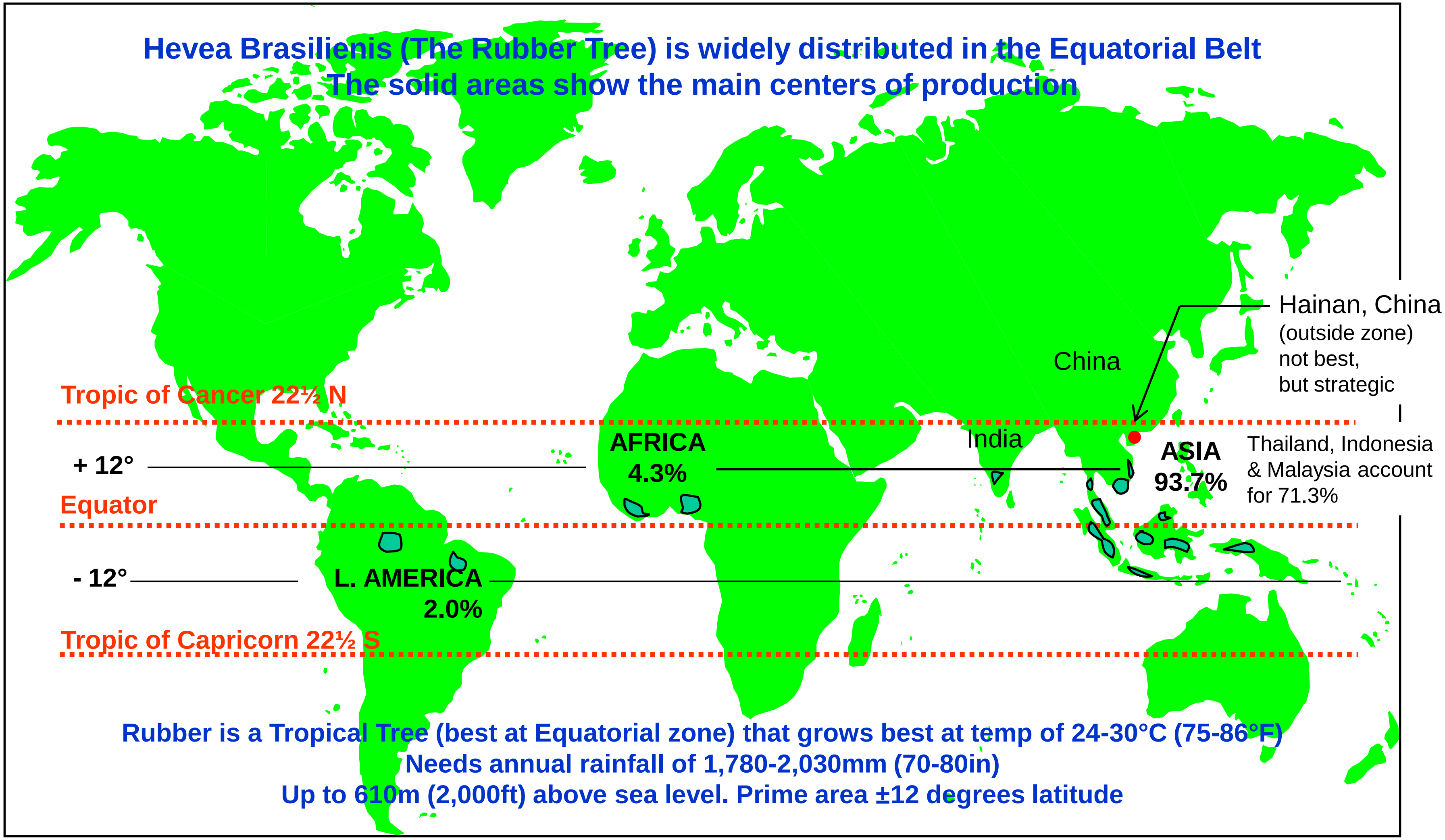
- Large volumes available
  - Global NR production is ~20 B lbs/yr
  - Approximately 70% is used to make tires
- Superior physical properties
  - Excellent resistance to wear and tear; low hysteresis
  - Essential for demanding applications (e.g., aircraft, military, trucks)
  - Major ingredient (25-50%) in better consumer tires
- No alternatives available at comparable price and volume
  - Commercial NR based on single species (i.e., *Hevea brasiliensis*)
  - Synthetic polyisoprene is best alternative but limited by relative scarcity of isoprene monomer

Threats to Supply of Natural Rubber

- Global demand increases well beyond supply
- Political instability in growing regions (Southeast Asia, W Africa)
  - Rubber trees grow in a very narrow band at +/- 12 degrees from the equator.
- Economic instability
  - Dominance of small holders
  - Economic alternatives from industrialization
- Widespread plant disease from lack of genetic diversity

Significant threats to NR supply exist

World Map Showing NR Production Regions



The Vision: Isoprene from Biomass

Biomass

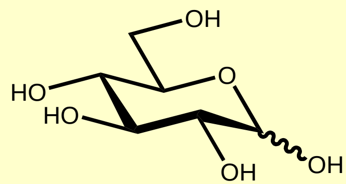
Corn

Switchgrass

Sugar cane Molasses

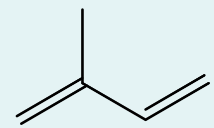
Woody biomass

Sugars



D-Glucose
+
other C5 and C6 sugars

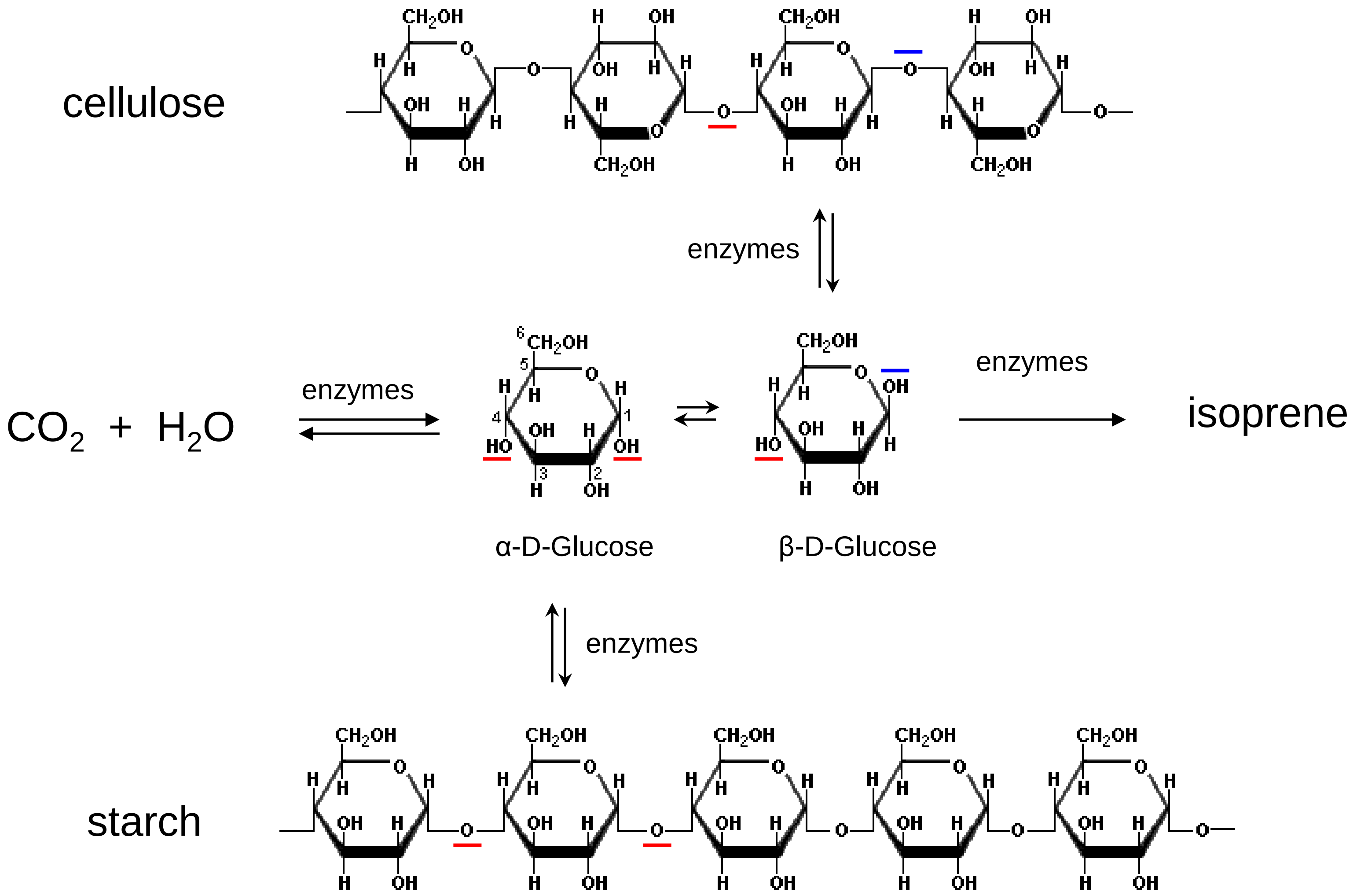
Isoprene



2-Methyl-1,3-butadiene

We aim to develop an efficient and sustainable fermentation route to isoprene from carbohydrate feedstocks

Biochemical Basis for Feedstock Conversion



Bioprocess to Isoprene Enables:

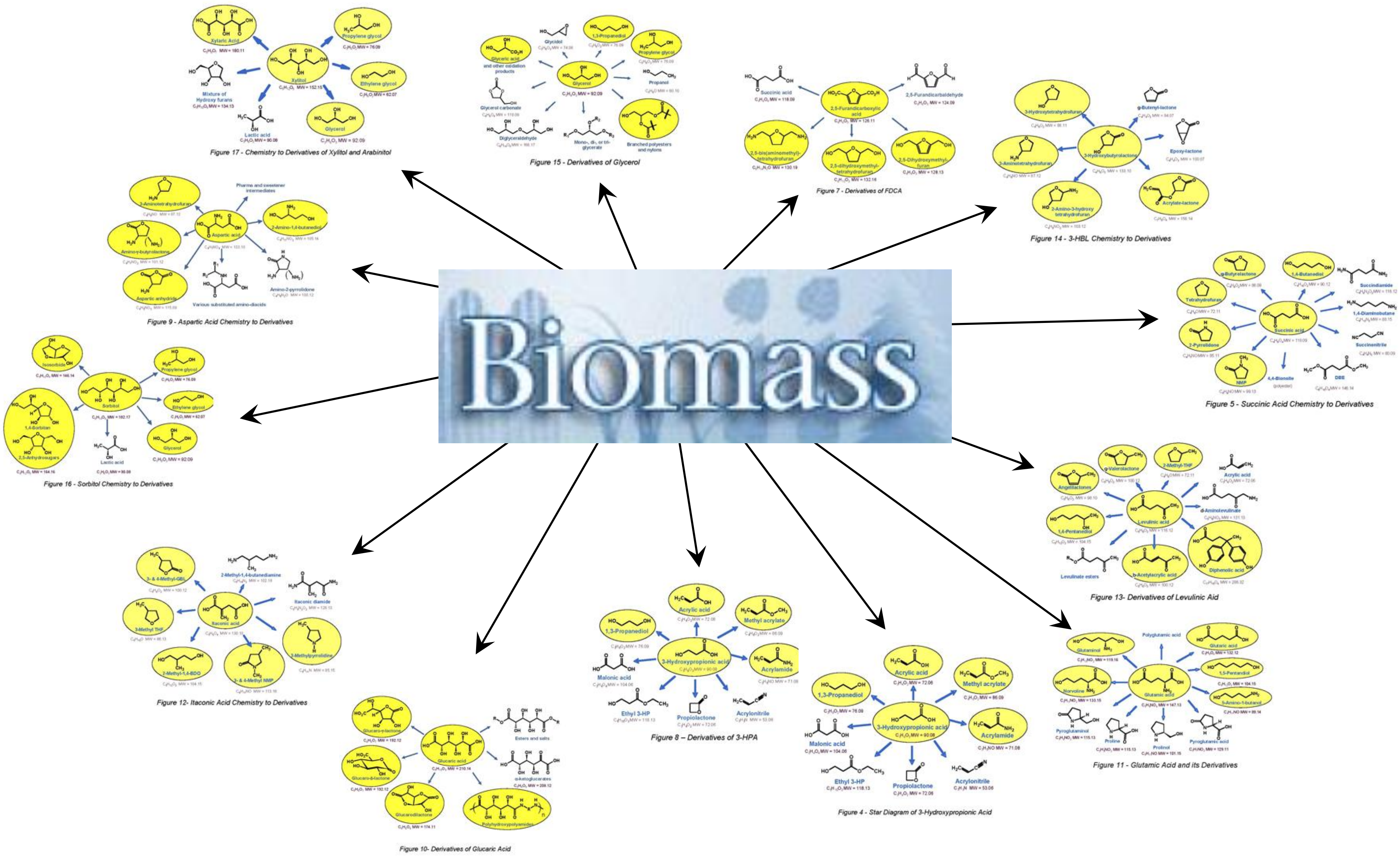
- Decreased dependence on natural rubber sourcing
- Reduced petroleum price impact on isoprene costs
- Supply of isoprene de-linked from petroleum processing
- Stability of monomer supply
- Potential for significant savings associated with rubber supply
- Potential for product performance enhancement

Synthetic rubber from sustainable nonpetroleum based sources

Isoprene Production

TREES	PETROLEUM CRACKING	CHEMICAL SYNTHESIS	BIOBASED PROCESS
			
• Slow • Not commercially relevant	• Extractive distillation from ethylene & propylene production • Price linked to oil prices • Moving to “light” streams	• High cost • Petroleum feedstocks • Mfg. infrastructure in Russia & Japan	• Renewable feedstocks • Biochemical and biofuel products

Building Block Biochemicals (2006):



Partnership for BioIsoprene™

Goodyear	Genencor (A Danisco Division) / DuPont
• Leading manufacturer of synthetic elastomers • Technology for producing synthetic polyisoprene • Expertise for isolating, purifying, handling, storing and shipping isoprene	• Leading industrial biotechnology company • Technology for producing genetically-modified organisms for industrial applications • Ability to develop complete process for producing isoprene from biomass

Collaborative research initiative with joint multimillion-dollar investments

Goodyear and Genencor leveraging each others' expertise . . .

Collaborative Research Initiative

GENENCOR®
A Danisco Division

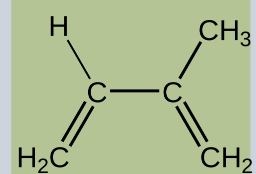
GENENCOR®
A Danisco Division

Renewable Feedstock(s)

Microbial Strain Development

Large Scale Fermentation

BioIsoprene™ recovery & purification knowhow

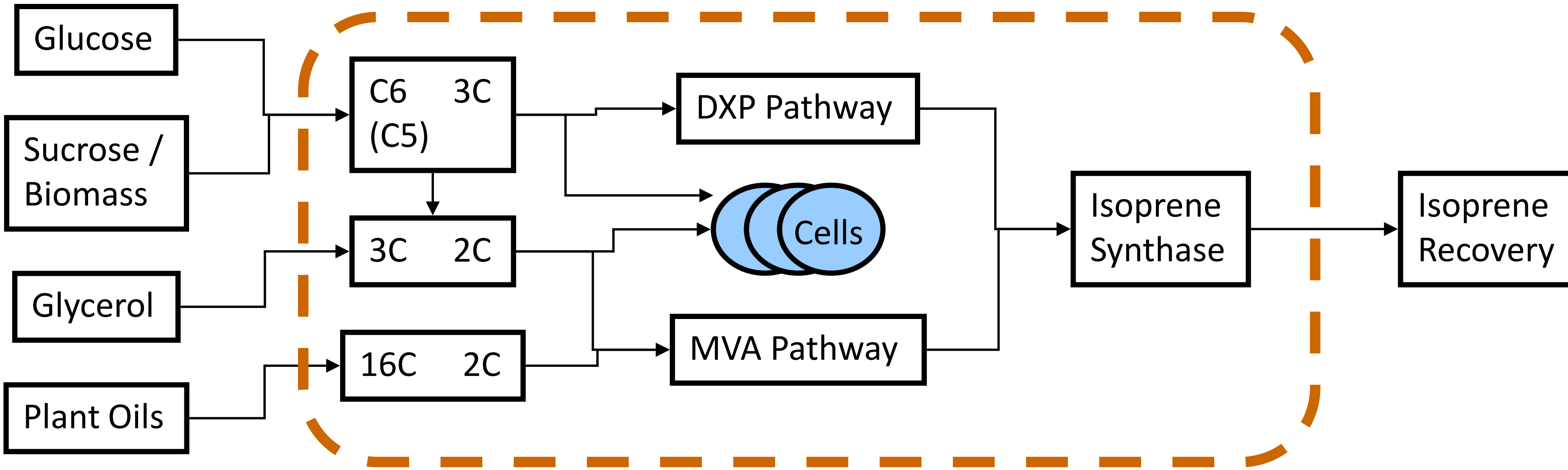


Polymer-Grade BioIsoprene™ Product

Integrated biobased process for production of BioIsoprene™

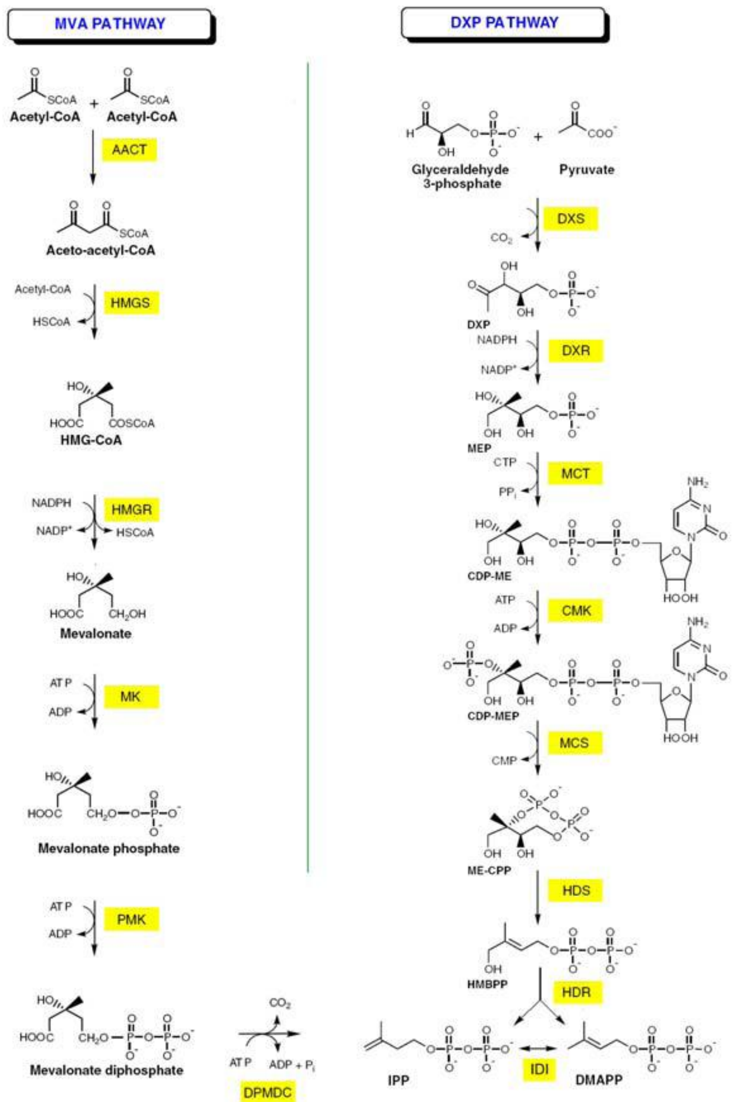
BioIsoprene™ Technology:

Conceptual View of Cell Factory



- Multiple feedstocks possible
- Two feeder pathways to isoprene precursor
- Isoprene synthase

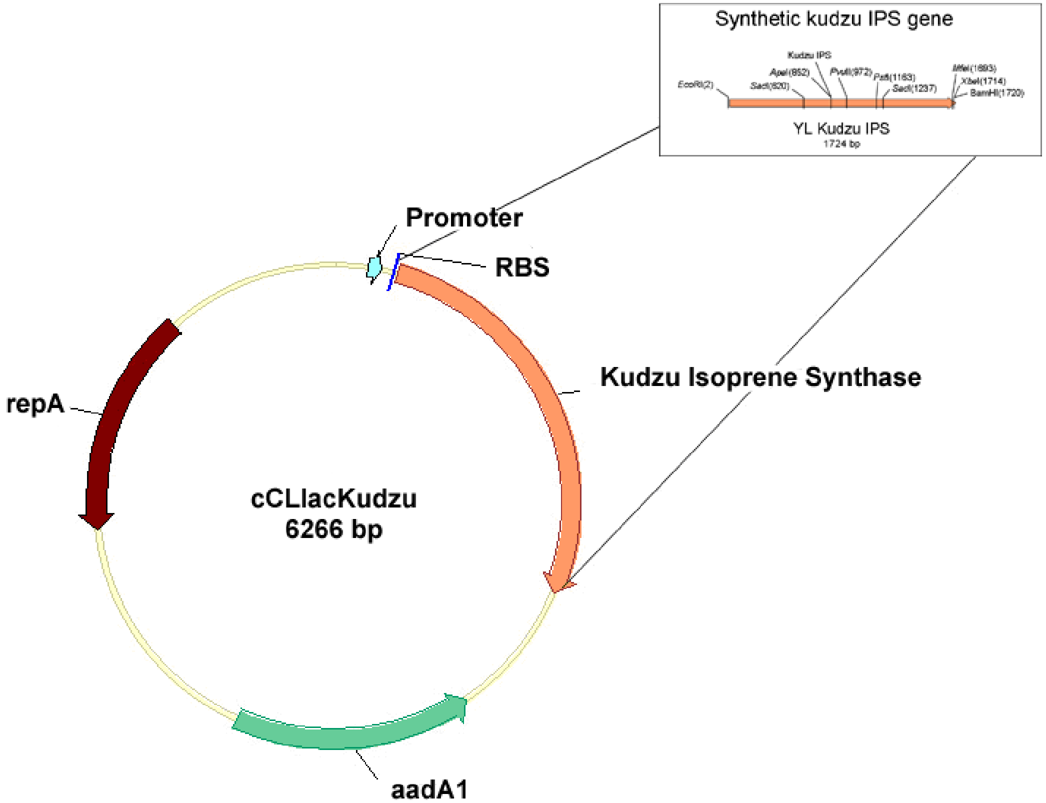
Metabolic Pathways



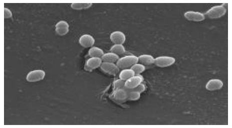
Bouvier (2005) *Prog. Lipid Res*. 44, 357–429.

- Two known pathways for producing precursors to isoprene (MVA, DXP)
- Both capable of using fermentable sugars as feedstocks
- Same isoprene-producing reaction

Genetic Engineering Optimizes Bacteria for Isoprene Production

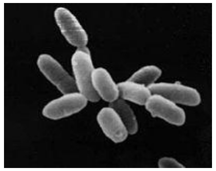


Enterococcus



Yeast

Archea



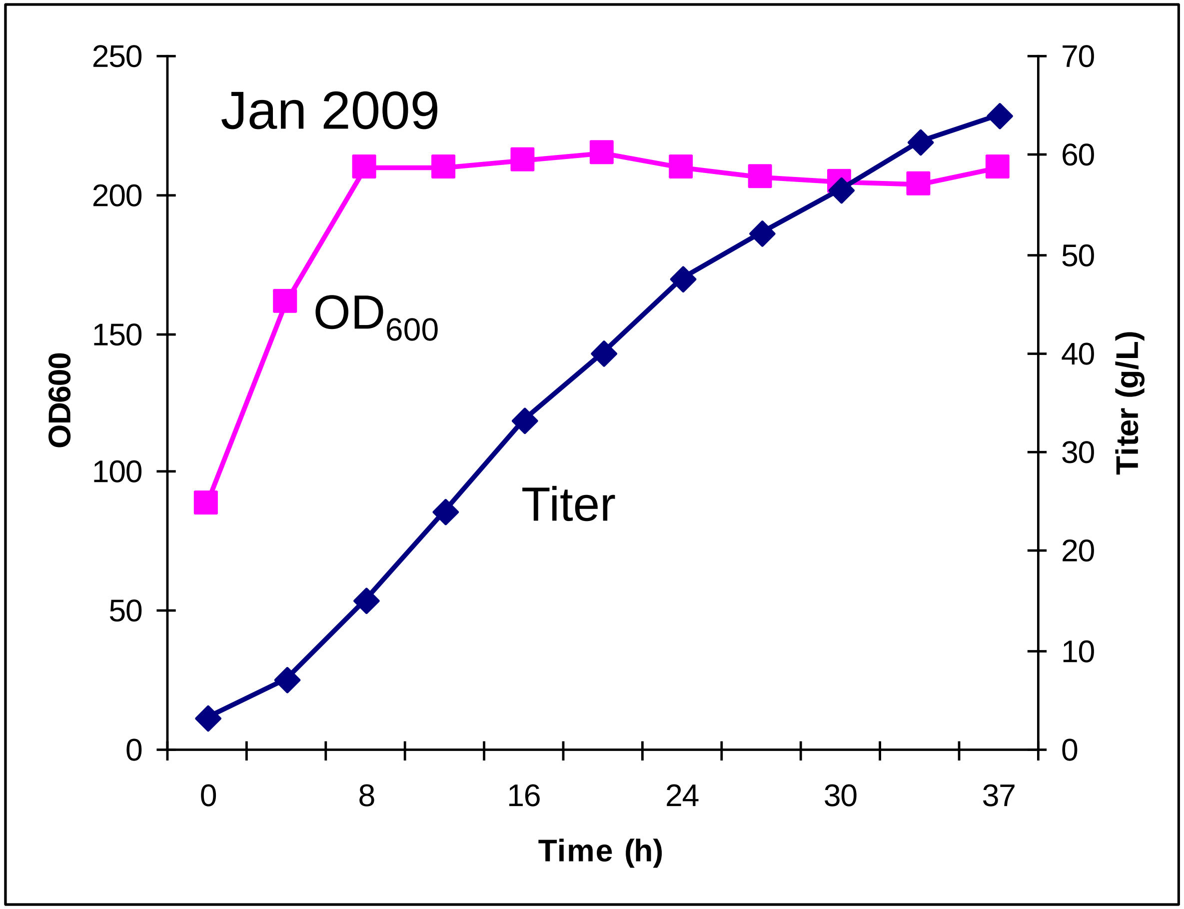
Kudzu

E. Coli

Genes from 5 different organisms were used to create the 1st-generation isoprene-producing bacteria

Isoprene Production

BioIsoprene™ Titer

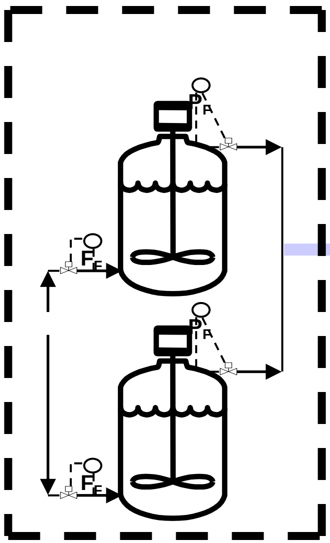


- Engineered *E. coli*
- 14-L fed batch fermentation from glucose
- Extensive IP portfolio: 14 published applications to date

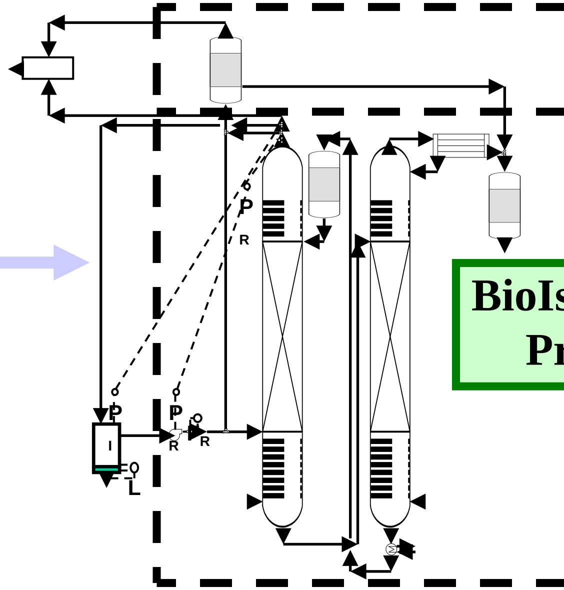
Integrated Process Overview

Feedstock

Fermentation



Recovery - Purification

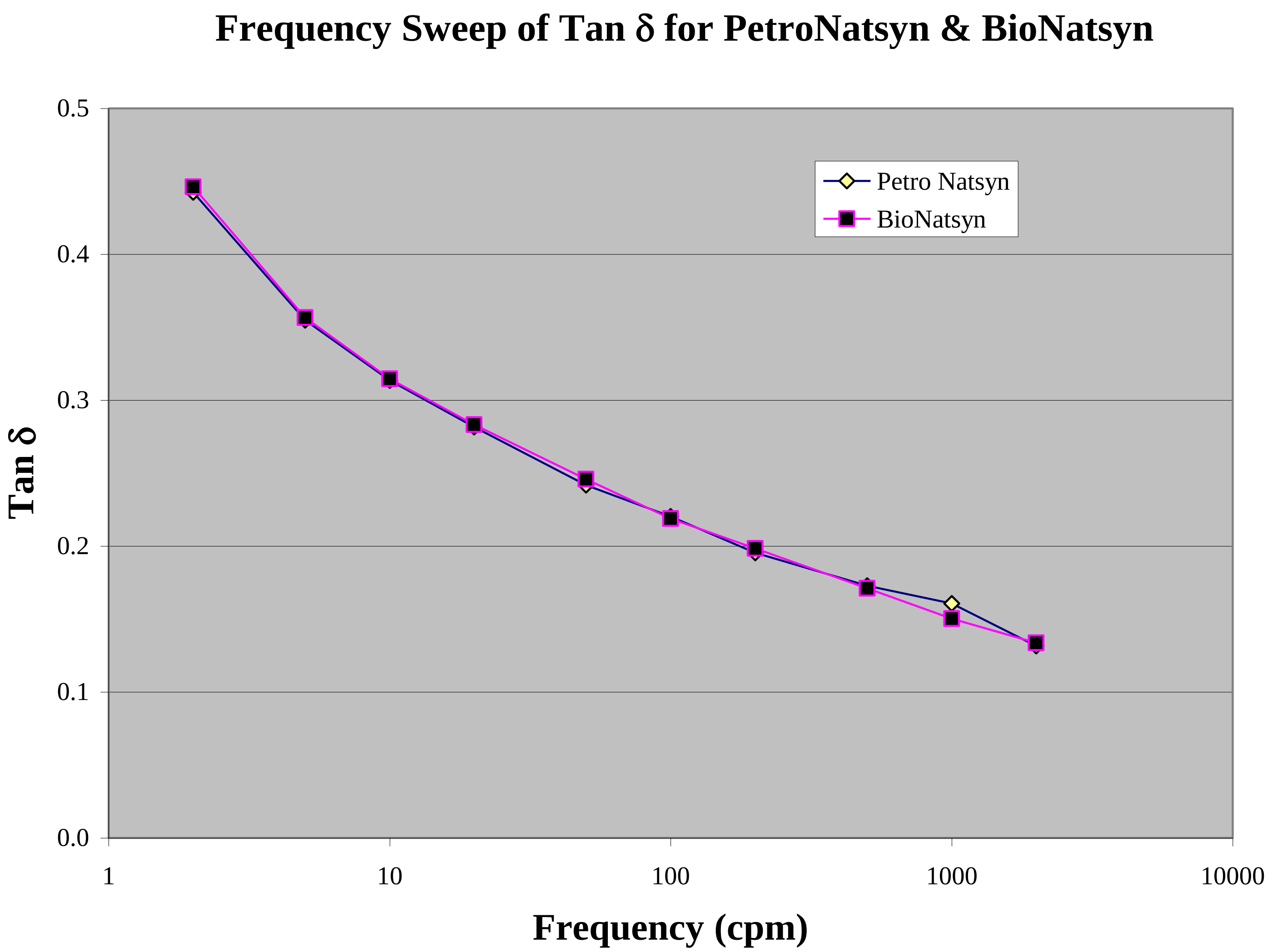


BioIsoprene™ Product

Polymerization

BioNatsyn™ (Synthetic Rubber)

BioIsoprene™ Polymerization



Tread Compound Properties

	BioNatsyn Polyisoprene	Natsyn Polyisoprene
Cure time, min (t_{90} at 150° C)	19.6	21.8
300% modulus, MPa	9.2	7.2
Tensile strength, MPa	16.5	16.1
Elongation at break, %	542	598
Mooney viscosity	45	45
Shore A hardness	71	62

The recipe consisted of 100 phr cis-1,4-polyisoprene, 60 phr carbon black, 12.5 phr silica, 13 phr oils and waxes, 8.25 phr antidegradants, 10.8 phr curatives

Concept Tire

2010 - Add isoprene to the list