SUSTAINABLE CHEMISTRY: HOW BIOLOGY IS SHAPING THE FUTURE OF CHEMICAL INDUSTRY

Science Day Lecture, Institute of Bioinformatics and Biotechnology

University of Pune

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JEWELS OF INDIAN SCIENCE IN PRE INDEPENDENT INDIA

- **C.V. Raman**
- **S. Ramanujan**
- **K.S. Krishnan**
- **S.N.Bose**
- **M. Visvesvaraya**
- **J.C. Bose**
- **Birbal Sahni**
- **P.C. Ray**
- **M.N. Saha**



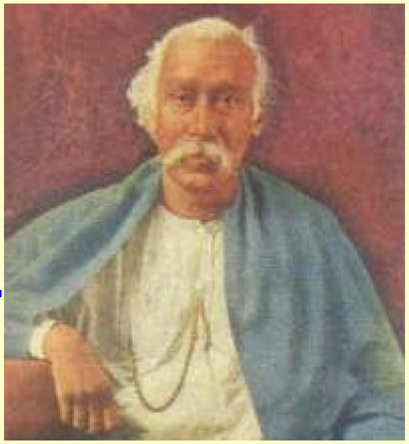







DR. MAHENDRALAL SIRCAR (1833-1904) and THE INDIAN ASSOCIATION FOR THE CULTIVATION OF SCIENCE(IACS)

1863	**Mahendralal stood first in M. D. Exam.**
1870	**Starts campaign for India's first Scientific Research Institute.**
1876	**IACS founded. Received no aid from British Government till 1926.**
1876-1904	**Lectures started. Laboratory/Library constructed. But no research!**
1907	**19 year old Raman starts research at IACS and receives the Nobel Prize in 1930.**



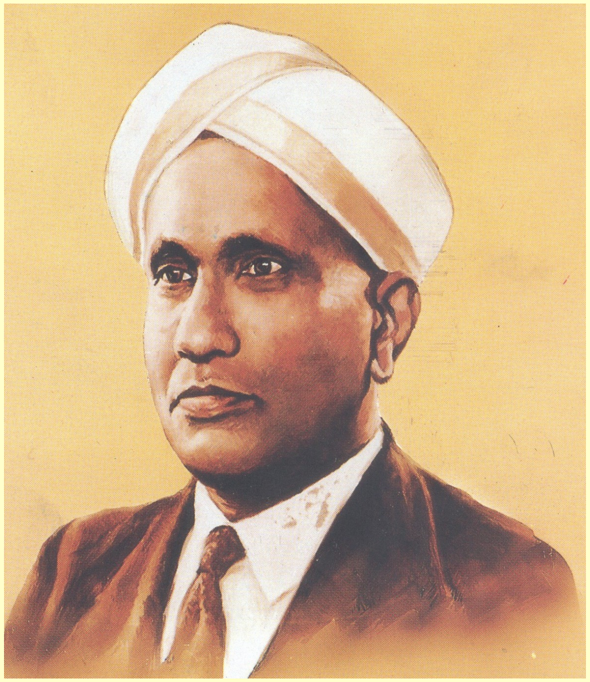
MAHENDRALAL'S VIEWS ON IACS

"The sole function will be science-learning & science- teaching. We should carry on unaided by the (British) Government or more properly speaking, without seeking its aid. I want *freedom* for the institution. I want it to be solely native and purely *National.*"

"I reiterate my conviction that if our country is to advance at all & take rank with civilized nations, it can only be by means of science. To this end, I've given the best portion of my life, but I am sorry to leave this world with the impression that my labours have not met with the success it deserves." (*Last letter*, Nov. 1903)

A. L. Sircar, Son of M.L. Sircar, 21 November 1907

"We have got a young student with fine intellect, doing research in our laboratory. A side issue of his work has been published in *Nature* (24 Oct, 1907). The prophecy of the great man (MLS) is now going to be fulfilled. If circumstances do not go against us, Raman will be the brightest ornament of IACS."



C. V. Raman
1888-1970

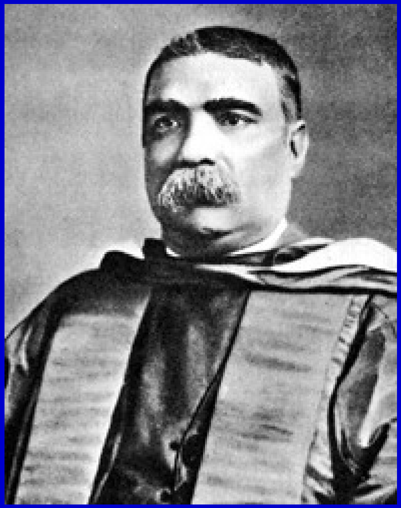
1906 Stood 1st in M.Sc. (did not attend classes!!
1907 Assistant Auditor General, AG`s Office, Calcutta
1907 Starts research at IACS and publishes the first paper

RAMAN ON MAHENDRALAL SIRCAR

"Dr. Sircar devoted a life-time of labour to the institution he created and equipped it for the advancement of science in India. Its doors were open awaiting the arrival of someone. That arrival happened to be myself. Sircar did not alas, live to see his aims accomplished.

(Reply to Civic Reception Given by Mayor of Calcutta, 1931)

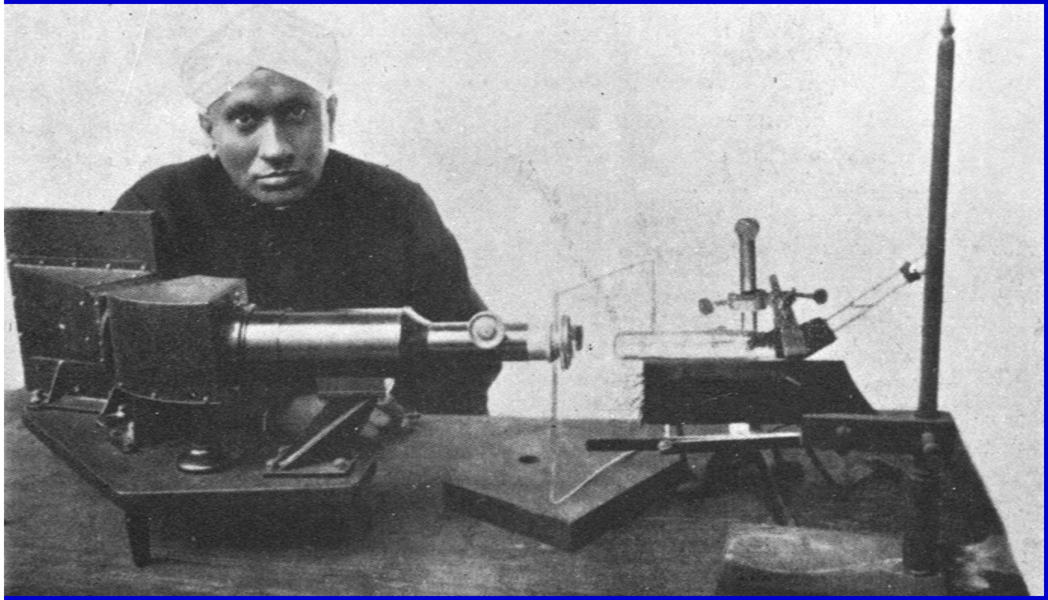
ASUTOSH ON RAMAN



Asutosh Mukherjee
(1864-1924)

"I admire the courage and spirit with which Raman exchanged a lucrative official appointment for a university Professorship. This instance encourages me to entertain the hope that there will be no lack of seekers of truth in the Temple of Knowledge which it is our ambition to erect."

"Sir Asutosh ventured to ask an young and unknown official to devote himself to the pursuit of knowledge under the aegis of the Calcutta University. This, on his part, was an act of courage. But for the action of Sir Asutosh, my scientific career would long ago suffered an abrupt termination."- C. V. Raman



THE RAMAN EFFECT

1928: Raman announced on 28 February, used sunlight & eyes
1930: Raman receives the Nobel Prize.
1998: *International Historic Chemical Landmark* (ACS)

On February 28, 1928, through his experiments on the scattering of light, he discovered the Raman Effect. It was instantly clear that this discovery was an important one. It gave further proof of the quantum nature of light. Raman spectroscopy came to be based on this phenomenon, and Ernest Rutherford referred to it in his presidential address to the Royal Society in 1929. Raman was confident of winning the Nobel Prize in Physics as well, and was disappointed when the Nobel Prize went to Richardson in 1928 and to de Broglie in 1929. He was so confident of winning the prize in 1930 that he booked tickets in July, even though the a wards were to be announced in November, and would scan each day's newspaper for announcement of the prize, tossing it away if it did not carry the news. He did eventually win the 1930 Nobel Prize in Physics "for his work on the scattering of light and for the discovery of the effect named after him. He was the first Asian and first non-White to get any Nobel Prize in the sciences. Before him Rabindranath Tagore had received the Nobel Prize for Literature.

I would like to stress the practical value of scientific researches to be carried out at in the National Chemical Laboratory, although I do not believe that utility is the main incentive to scientific work. It is in man's attempts to study nature and to understand her secrets that science finds its best motive. For this reason, I believe that good laboratories alone are not sufficient to produce scientific work but it is the ability of the individuals who work in the laboratory that counts.

I am sure that individuals of exceptional ability will work in the NCL and work for the advancement of science

Sir C.V. Raman, NL
January 3, 1950, Pune

SUCCESS IN SCIENCE

- **"Principle requisite for success in research is not maturity of knowledge but the freshness of outlook which is the natural attribute of youth."**
- **"Indian mind is not inferior, what we lack is courage and a spirit of victory. If that indomitable spirit were to arise nothing can hold us from achieving our rightful destiny."**

Sir C V Raman

SUSTAINABLE DEVELOPMENT (CHEMISTRY)

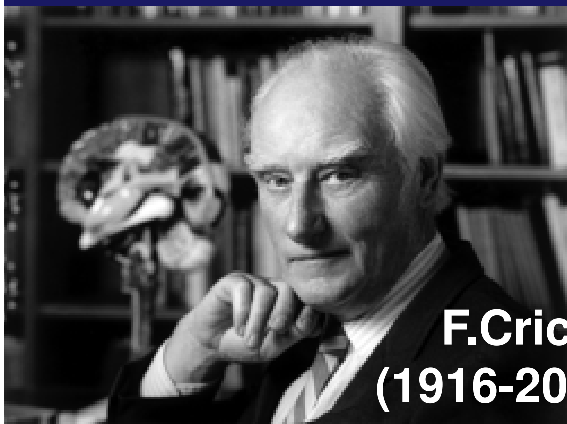
"Development (chemistry or chemical industry) that meet the needs of the present without compromising the ability of future generations to meet their own needs"

In other words, each generation must bequeath to its successor at least as large a productive base it inherited from its predecessor

Brundtland Report
UN World Commission on Environment and Development, 1987

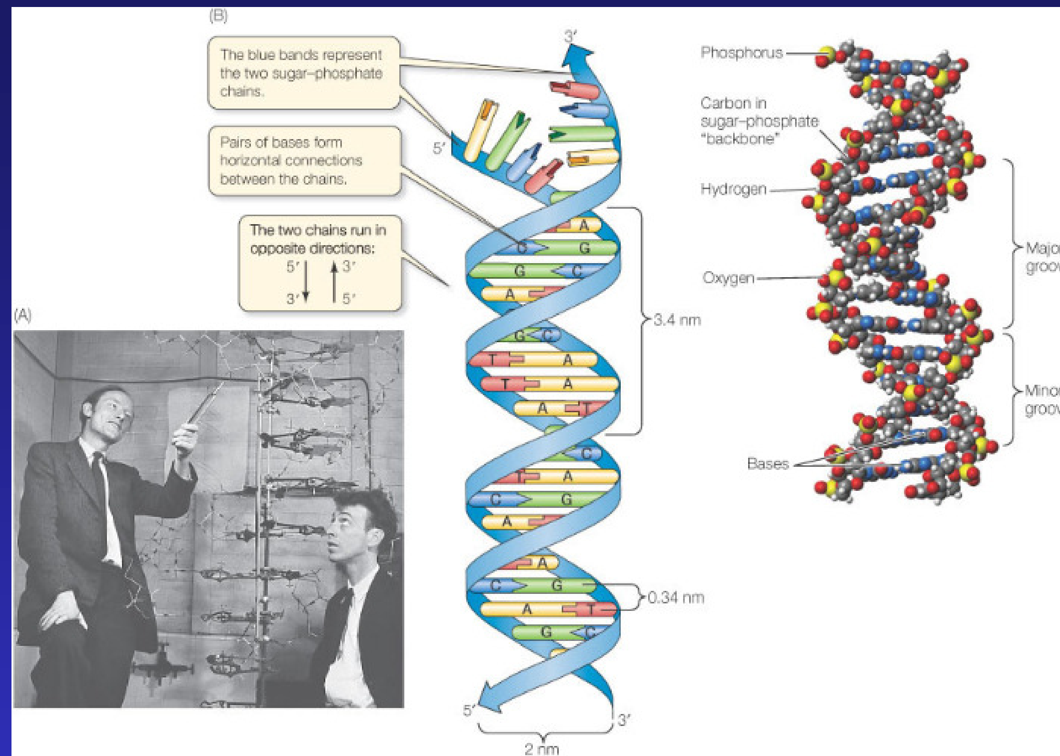
www.un.org/documents/ga/res/42/ares 42-187.htm

28 FEBRUARY 1953 : ANOTHER HISTORIC DAY FOR SCIENCE



F.Crick (1916-2004)

J.D.Watson (1928-)

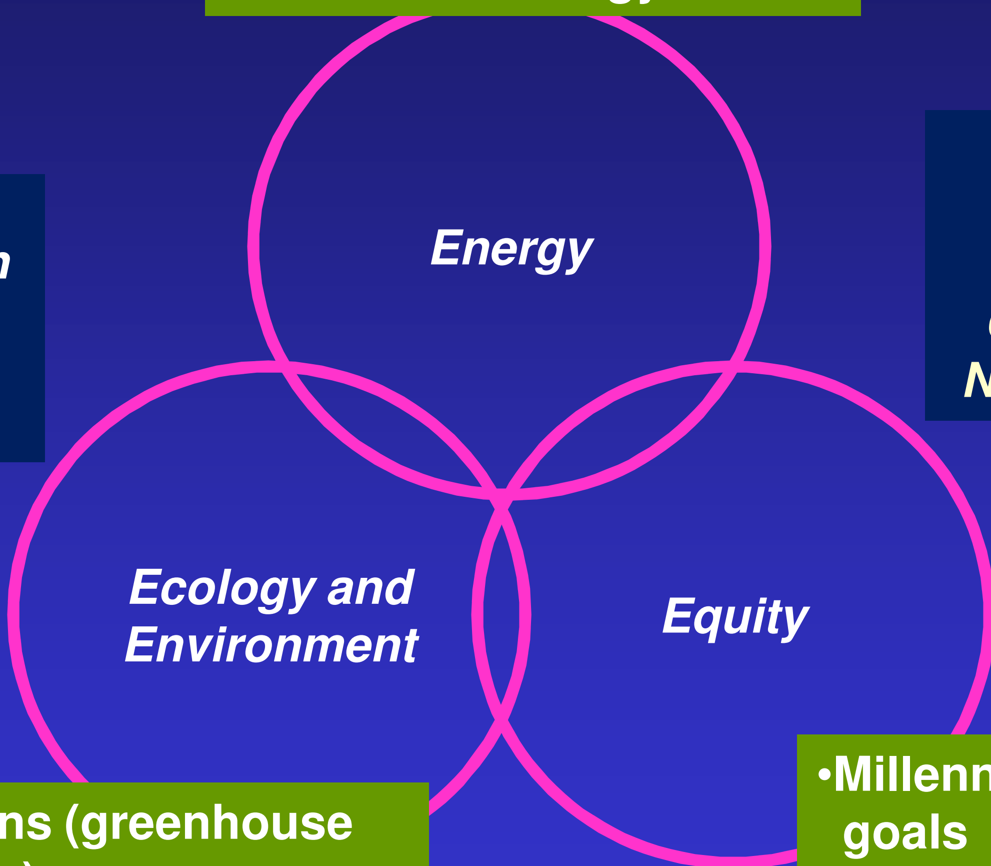


"This structure has novel features which are of considerable biological interest"………It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material"

Watson and Crick in Nature, April 25, 1953

- Clean energy
- Energy efficiency
- Renewable energy

Our civilization is at historic crossroads



Key : Sustainable Consumption Conservation of Natural Resources

- Reduced emissions (greenhouse gas/carbon dioxide)
- Materials from renewable resources
- De-carbonization

- Millennium development goals
- Access and entitlement
- Equitable distribution
- Climbing the economic ladder

THE STRUCTURE OF THE CHEMICAL INDUSTRY

Crude Oil

93%

7%

Feed-stocks

fuel (energy)

Chemicals

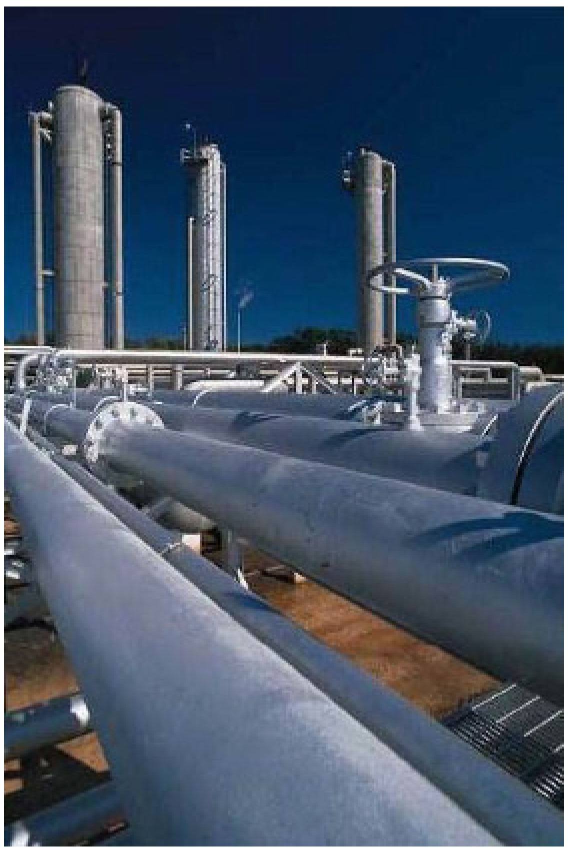
Polymers

Transportation & heating

Specialties

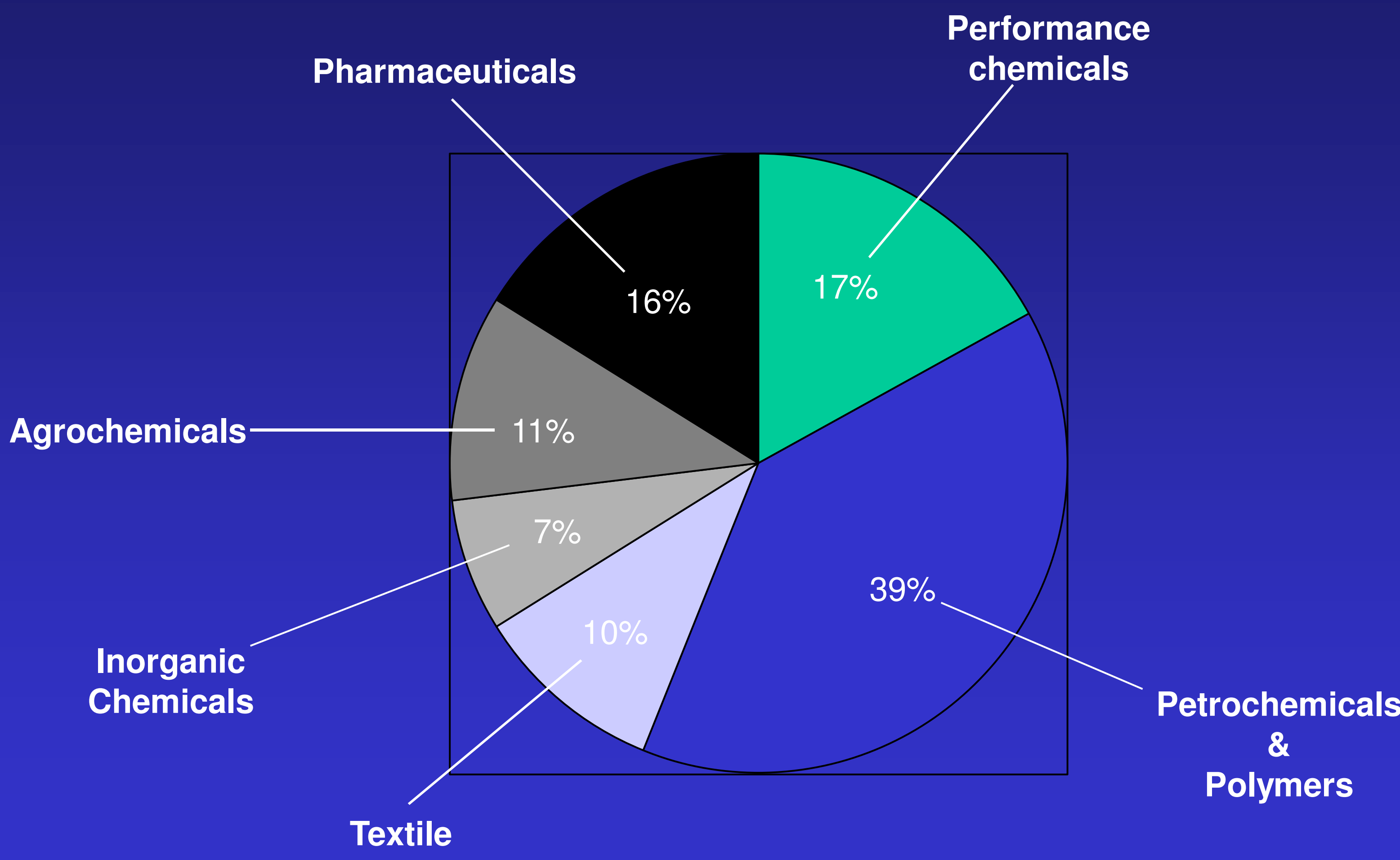
Synthesis

Pharmaceuticals



WORLD CHEMICALS MARKET

A THREE TRILLION $ INDUSTRY



CHEMICALS AND MATERIALS

- **Exclusive dependence on fossil based resources**
- **Anthropogenic emissions of carbon dioxide**
- **Generation of wastes that need disposal**
- **Large use of water**
- **Persist in the environment**

Can the materials needs of man be based on the concept of sustainability of both resources and environment?

GLOBAL CARBON CYCLES : THE KINETIC CONUNDRUM

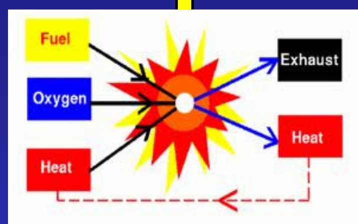
CO_2

Carbohydrates (Biomass)

millions of years (heat, pressure)

Hydrocarbons

Fuels
Chemicals
Polymers

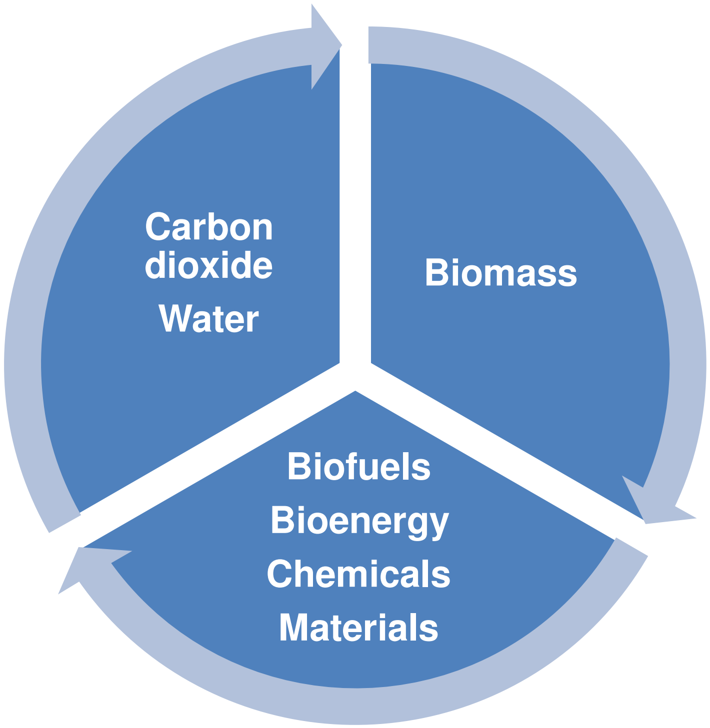


<10 years

We release more CO_2 than nature can sequester !

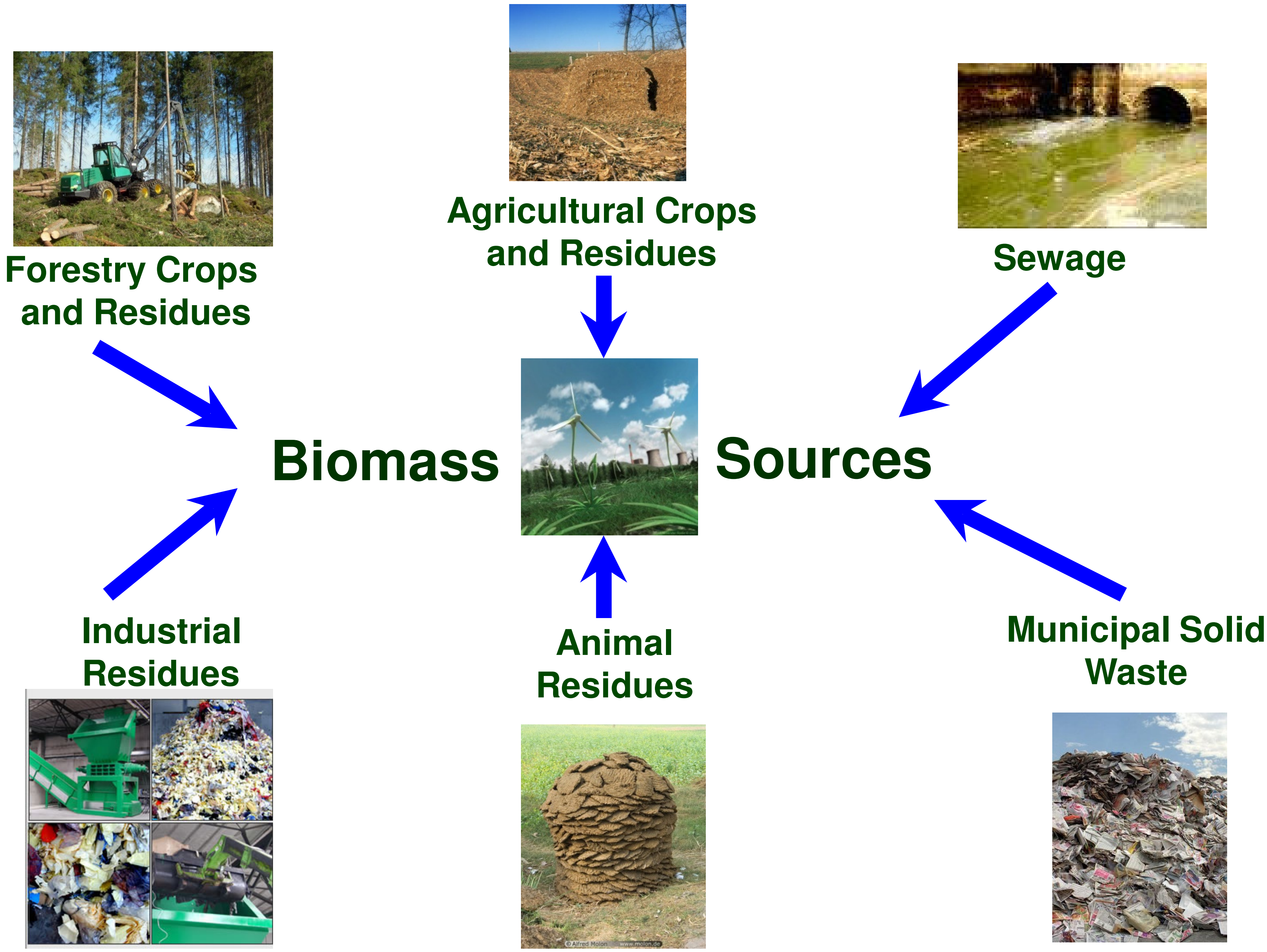
FROM HYDROCARBONS TO CARBOHYDRATES : REAPING THE BENEFIT OF RENEWABLE RESOURCES

- **The chemical industry is increasingly focused on the concept of sustainability**
- **There is only so much fossil fuels on earth and with time oil will become increasingly scarce**
- **Chemicals / feed stocks manufacturing will progressively shift to natural gas in the short term and renewable carbohydrate resources (biomass) in the long term**



Is such a virtuous cycle just a dream ?

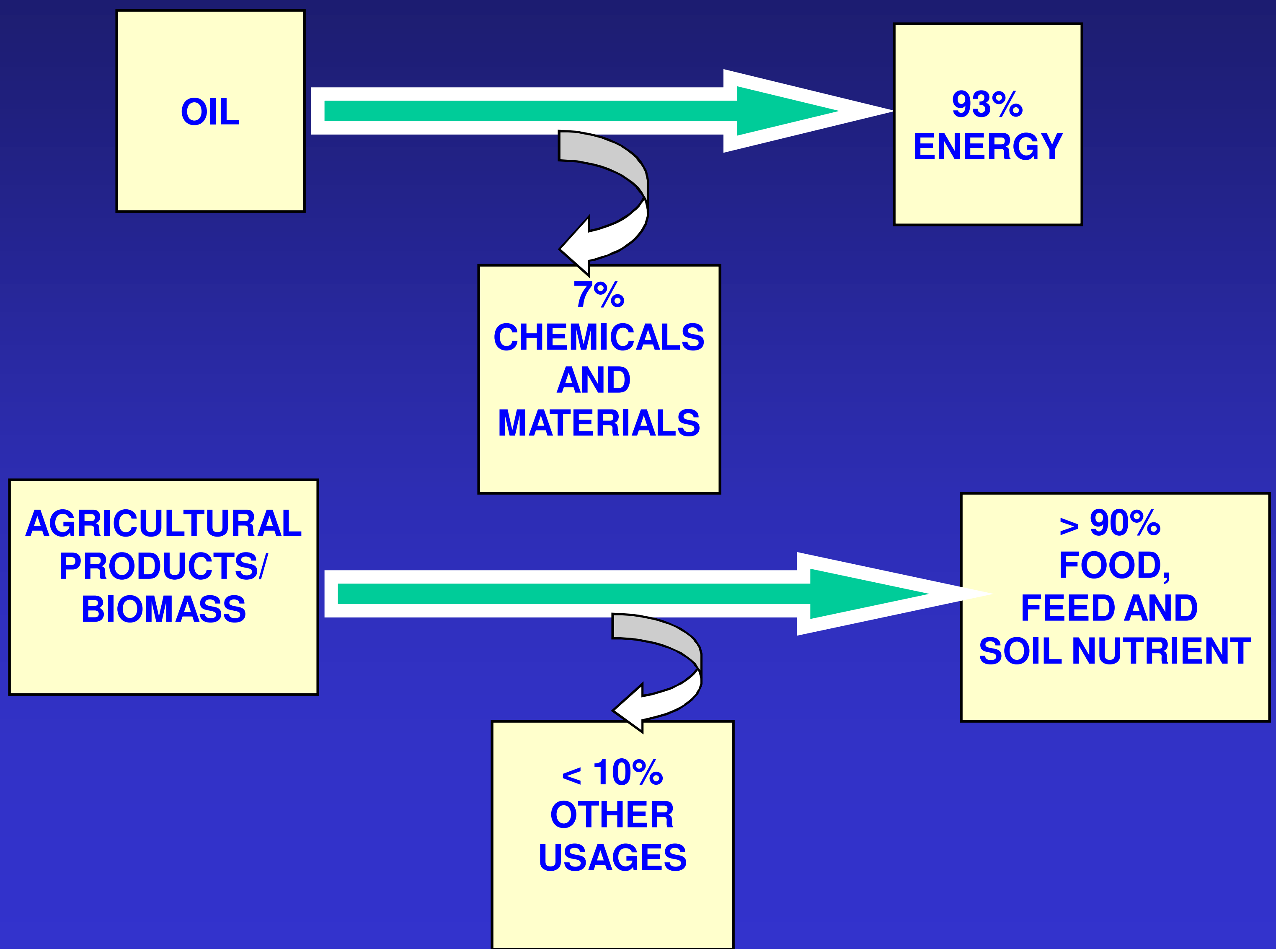
WHERE DOES BIOMASS COME FROM ?



OPPORTUNITIES IN BIOMASS

- **Bio-fuels**
- **Bio-power (heat and electricity)**
- ***Bio-derived chemicals and materials***

USE OF CARBON CONTAINING RAW MATERIALS



FOOD versus FUEL

April 7, 2008

• Using land to grow crops for fuels lead to destruction of forests, wetlands and grasslands that store enormous amount of carbon

Corn diverted to fuel ethanol in USA

↓

Soyabean growers switch to corn in USA

↓

Farmers in Brazil plant soyabean in land previously used as cattle pasture lands

↓

Leads to clearing of forest lands in Amazon rain forest

Law of unintended consequences !

BIO-REFINERY : A PLATFORM FOR SUSTAINABLE CHEMISTRY

The refinery based on fossil resources

Source	Transformation	Products	Downstream process
Oilfields	Refining & Cracking	Chemical Transformation	Formulation
Native Oil	Naphtha	Monomers & polymers	End Product

The bio-refinery based on renewable resources (cereals)

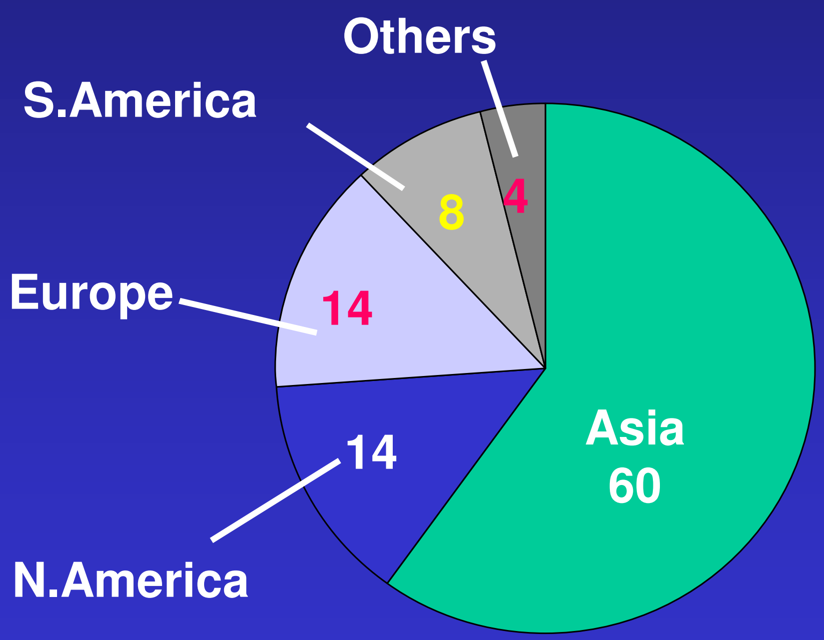
Source	Transformation		Products	Upstream process
Agricultural fields	Starch production	Biotech Trans-formation	Chemical Trans-formation	Formulation
Maize/Wheat	Glucose	Monomers & polymers		End Product

- Leading role of biotechnology
- Shared role between biotechnology and chemistry
- Leading role of chemistry

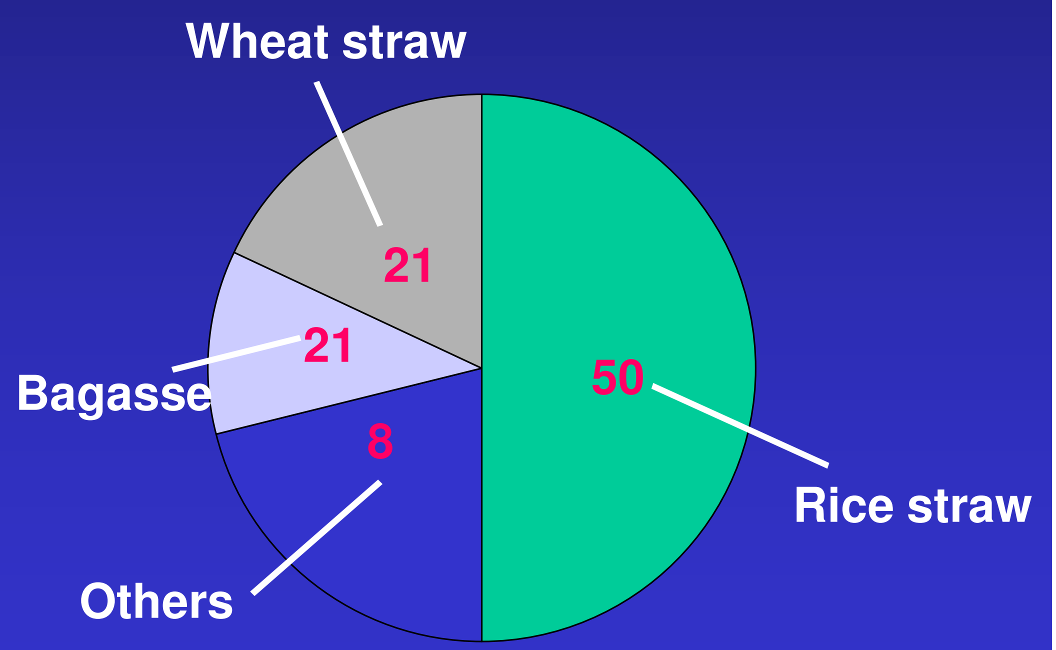
WORLD - WIDE AVAILABILITY OF AGRICULTURAL RESIDUES

Crop residues : > 2 billion tons

An unique Indian advantage ?

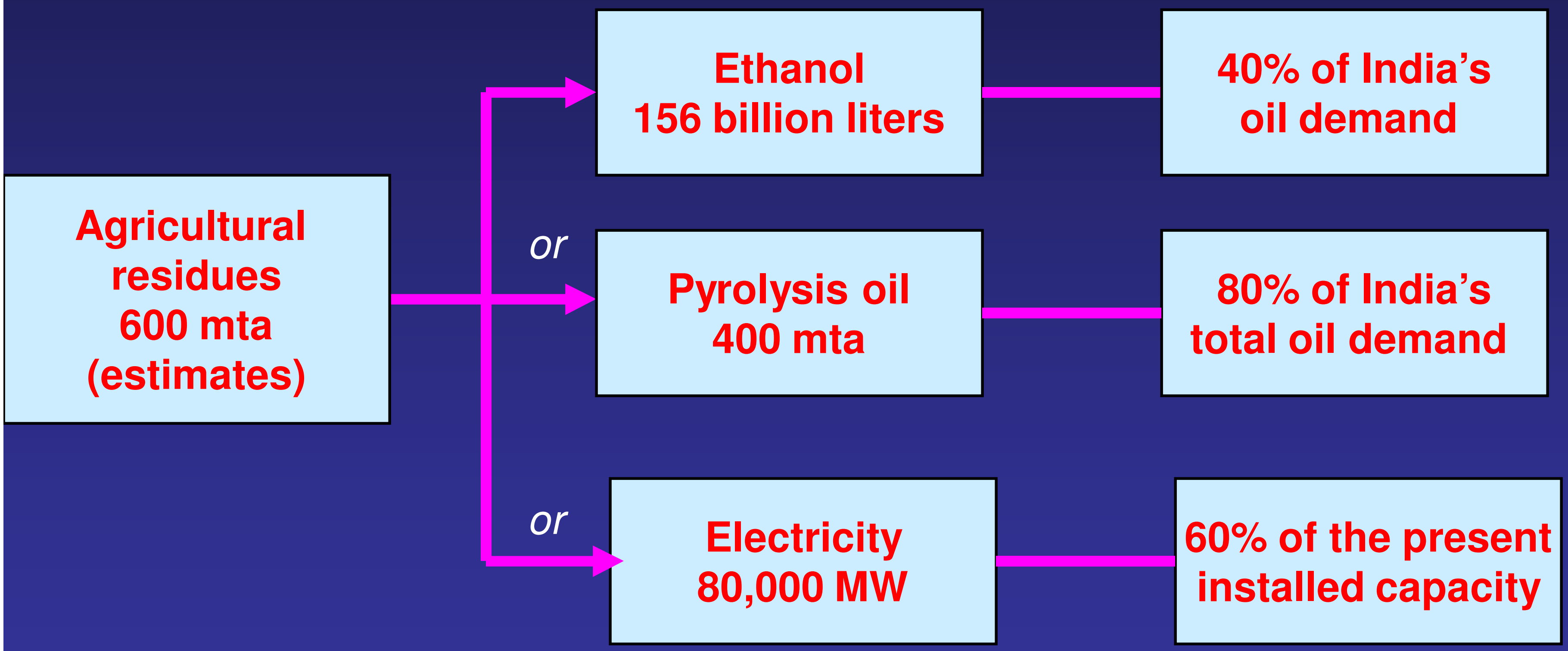


By Geography

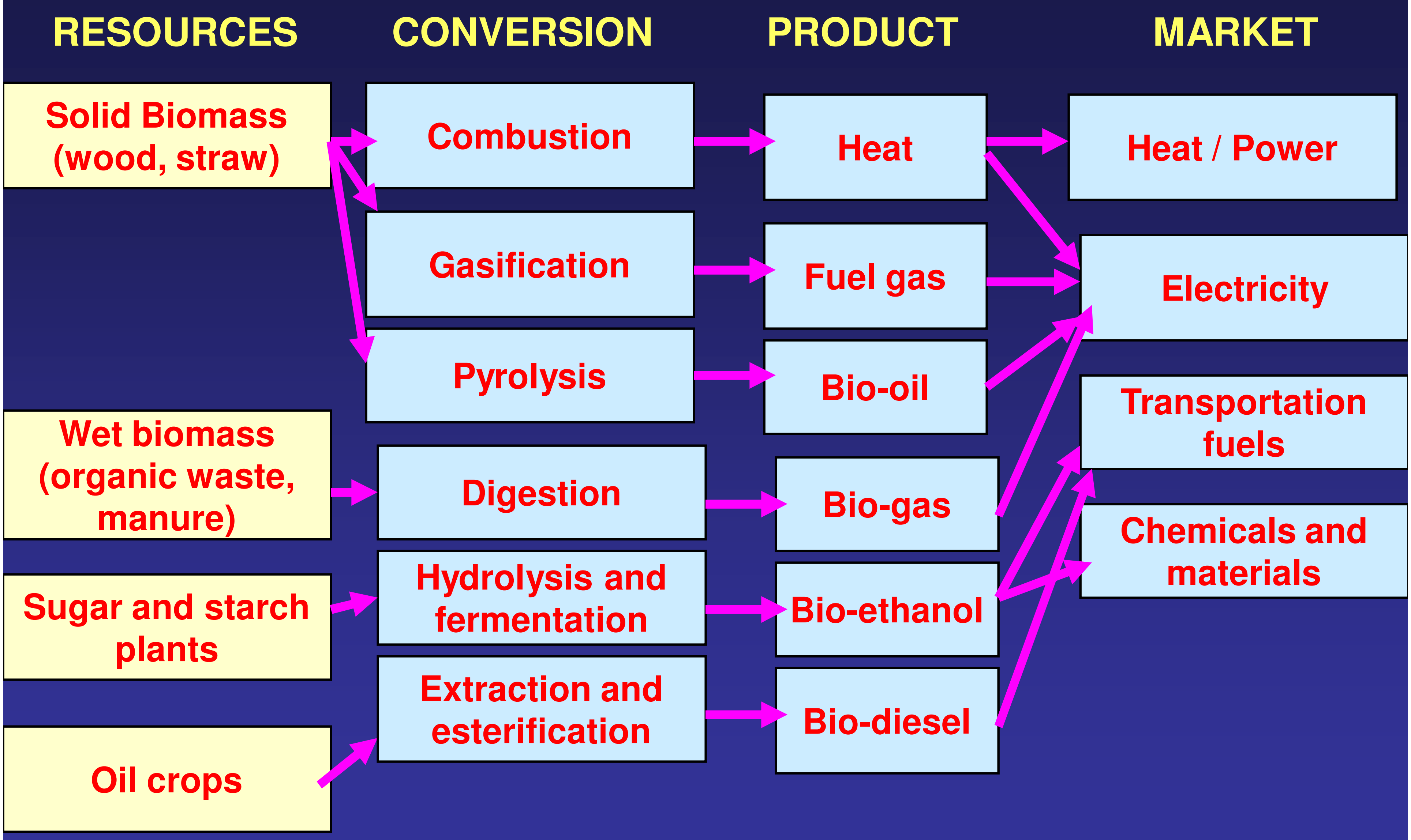


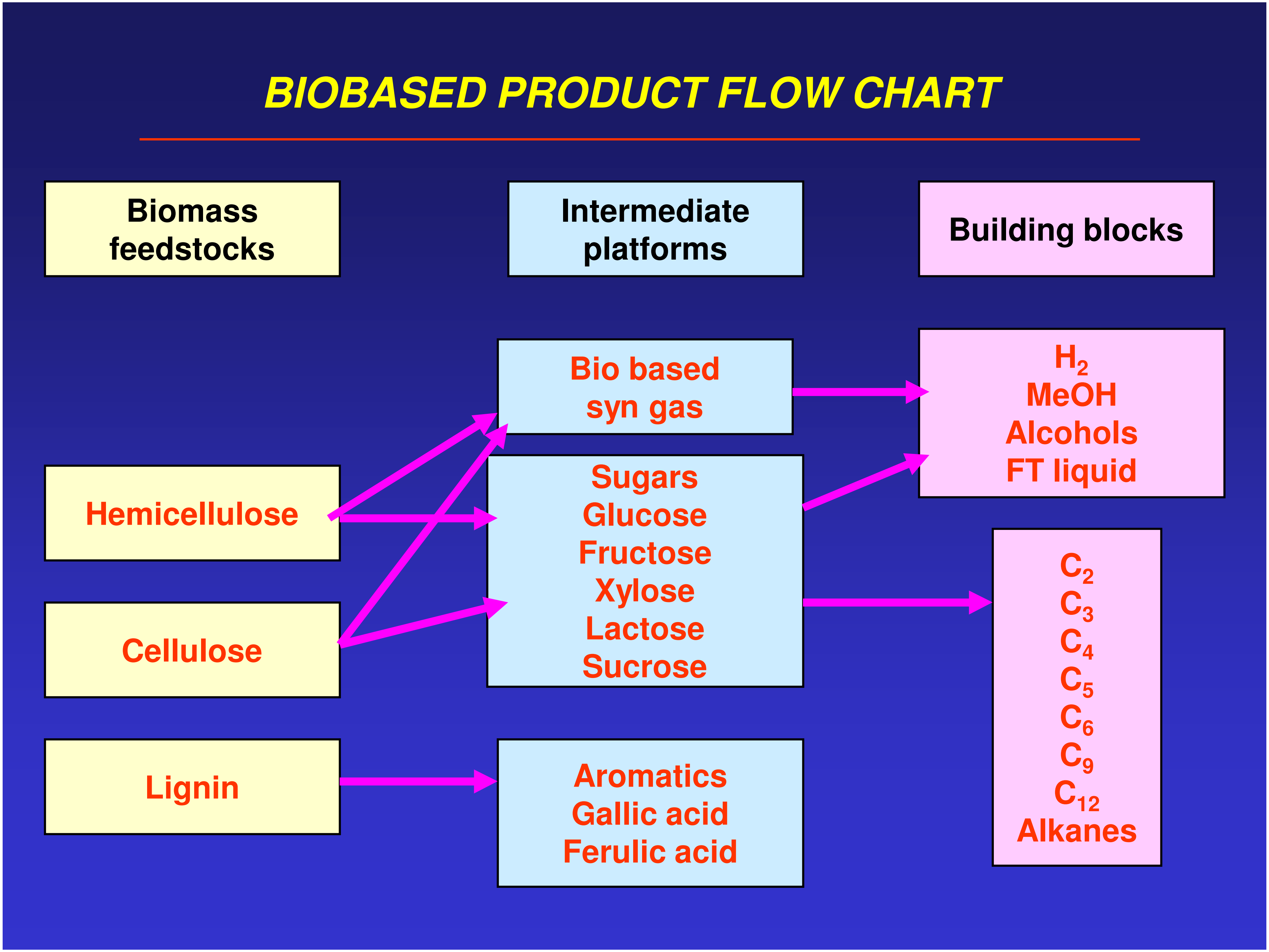
By type

AGRICULTURAL RESIDUES : INDIAN PERSPECTIVE



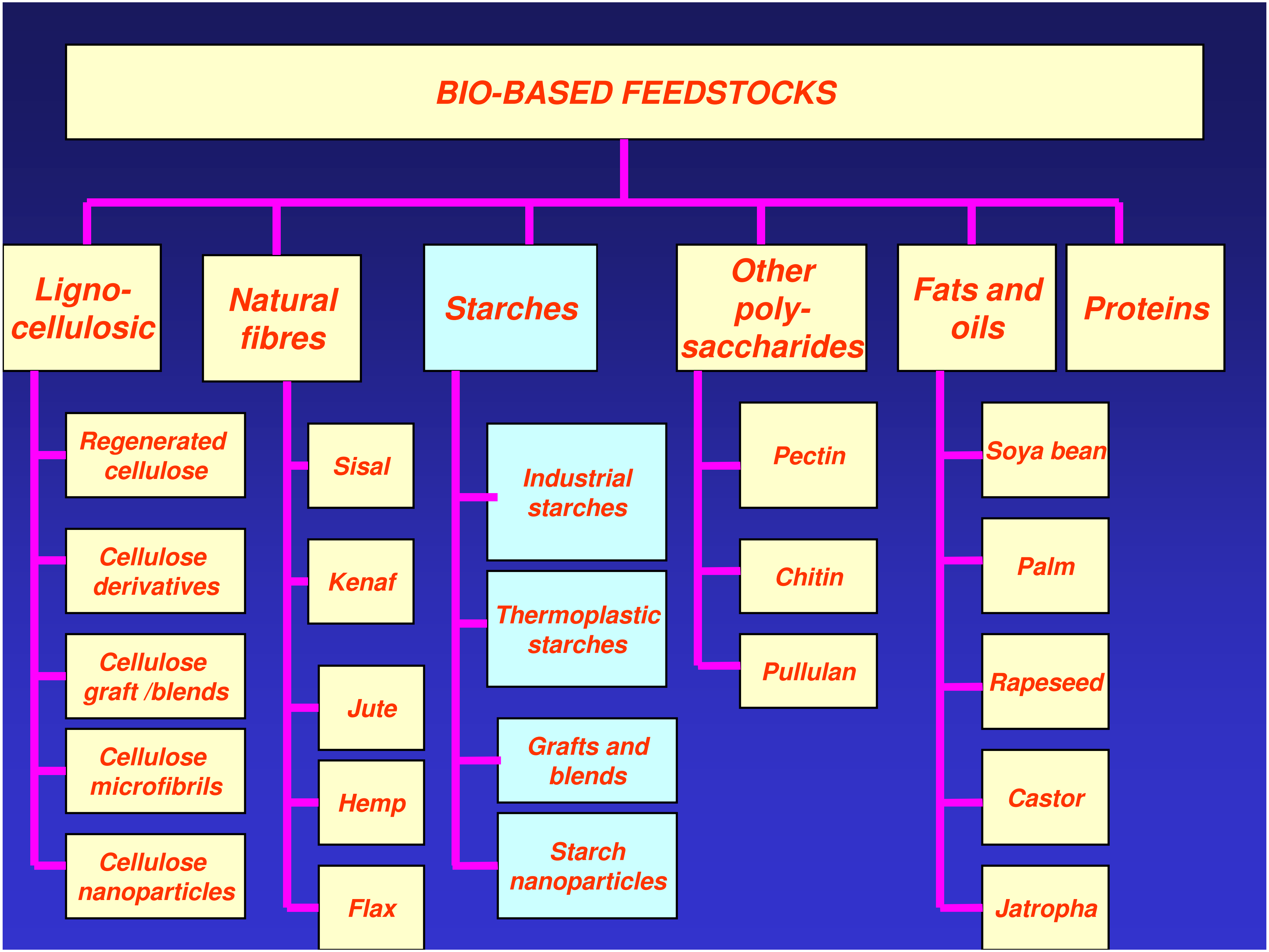
BIOMASS PATHWAYS




BIOBASED PRODUCT FLOW CHART
Biomass feedstocks
Intermediate platforms
Building blocks
Hemicellulose
Cellulose
Lignin
Bio based syn gas
Sugars
Glucose
Fructose
Xylose
Lactose
Sucrose
Aromatics
Gallic acid
Ferulic acid
H_2
MeOH
Alcohols
FT liquid
C_2
C_3
C_4
C_5
C_6
C_9
C_{12}
Alkanes

BIO BASED CHEMICALS

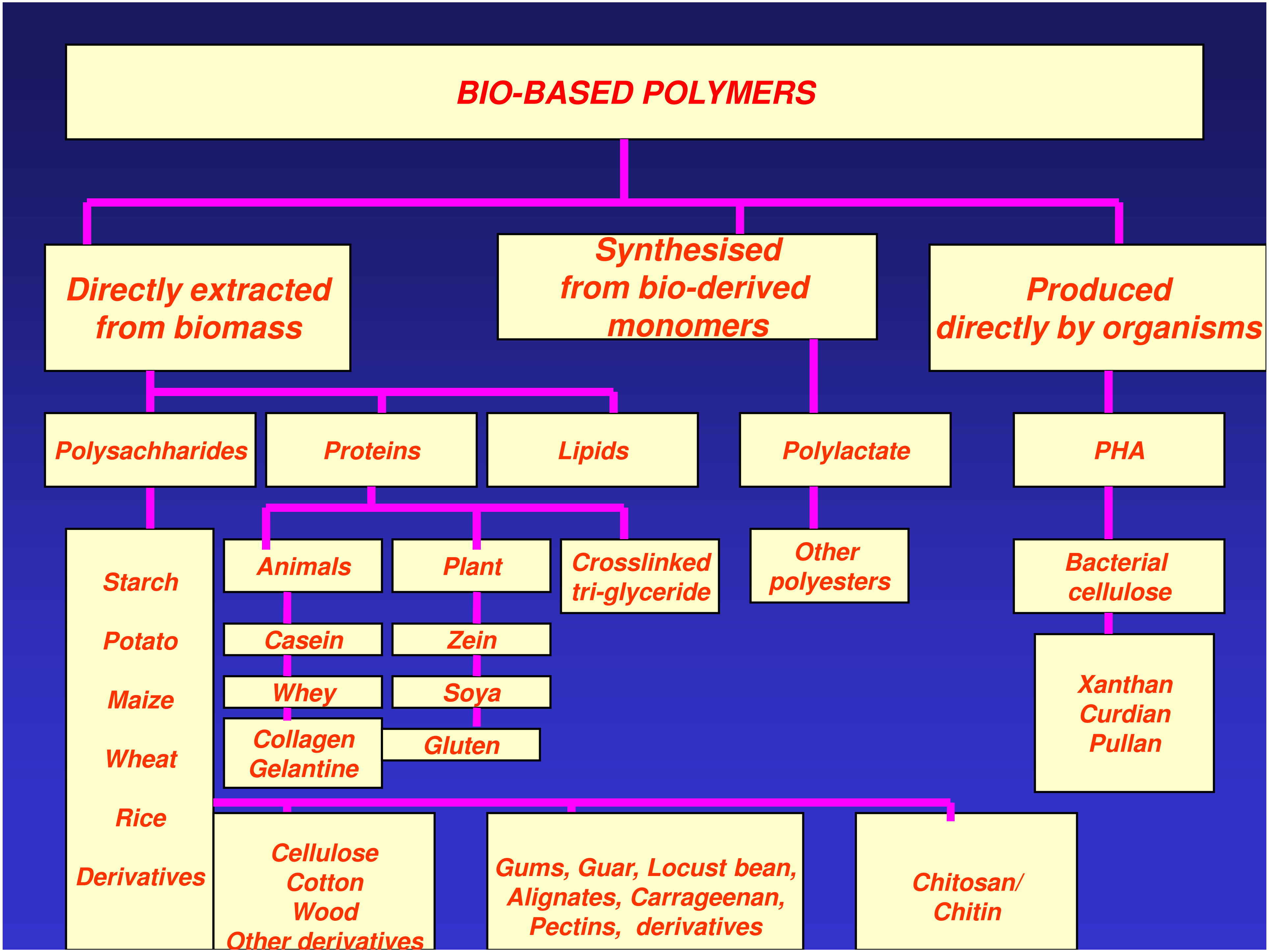
C_1 / C_2	C_3	C_4	C_5	C_6
Formaldehyde Acetaldehyde Ethanol	Glycerol Lactic acid 3-Hydroxy propionic acid Propionic acid Malonic acid Serine	Succinic Fumaric Malic Aspartic 3-Hydroxy butyro lactone Acetoin Theorine	Itaconic Furfural Levulinic acid Glutamic Xylitol	Citric 5-Hydroxy methyl furfural Gluconic Lysine Sorbitol

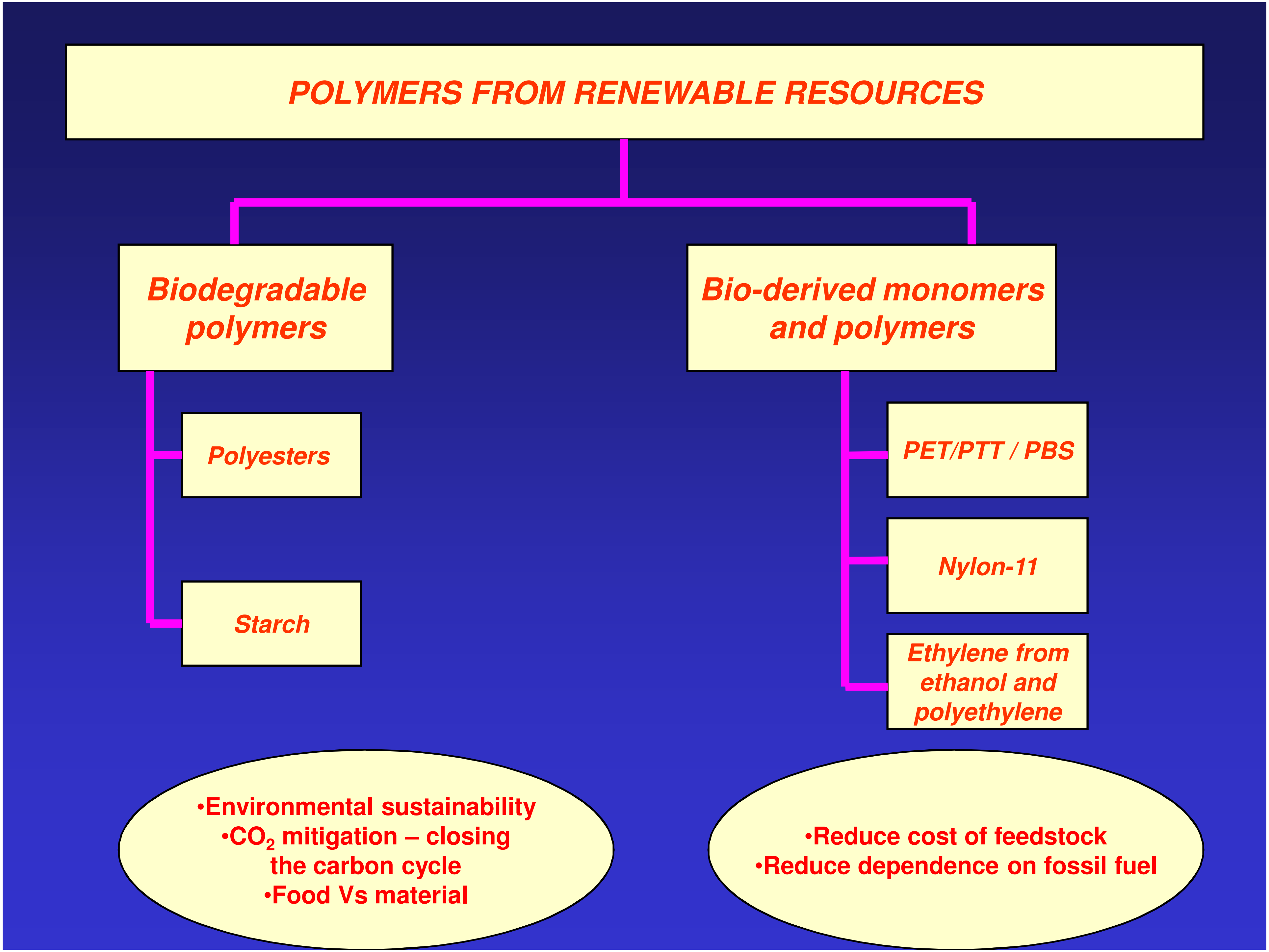

BIO-BASED FEEDSTOCKS
Ligno-cellulosic
Regenerated cellulose
Cellulose derivatives
Cellulose graft /blends
Cellulose microfibrils
Cellulose nanoparticles
Natural fibres
Sisal
Kenaf
Jute
Hemp
Flax
Starches
Industrial starches
Thermoplastic starches
Grafts and blends
Starch nanoparticles
Other poly-saccharides
Pectin
Chitin
Pullulan
Fats and oils
Soya bean
Palm
Rapeseed
Castor
Jatropha
Proteins

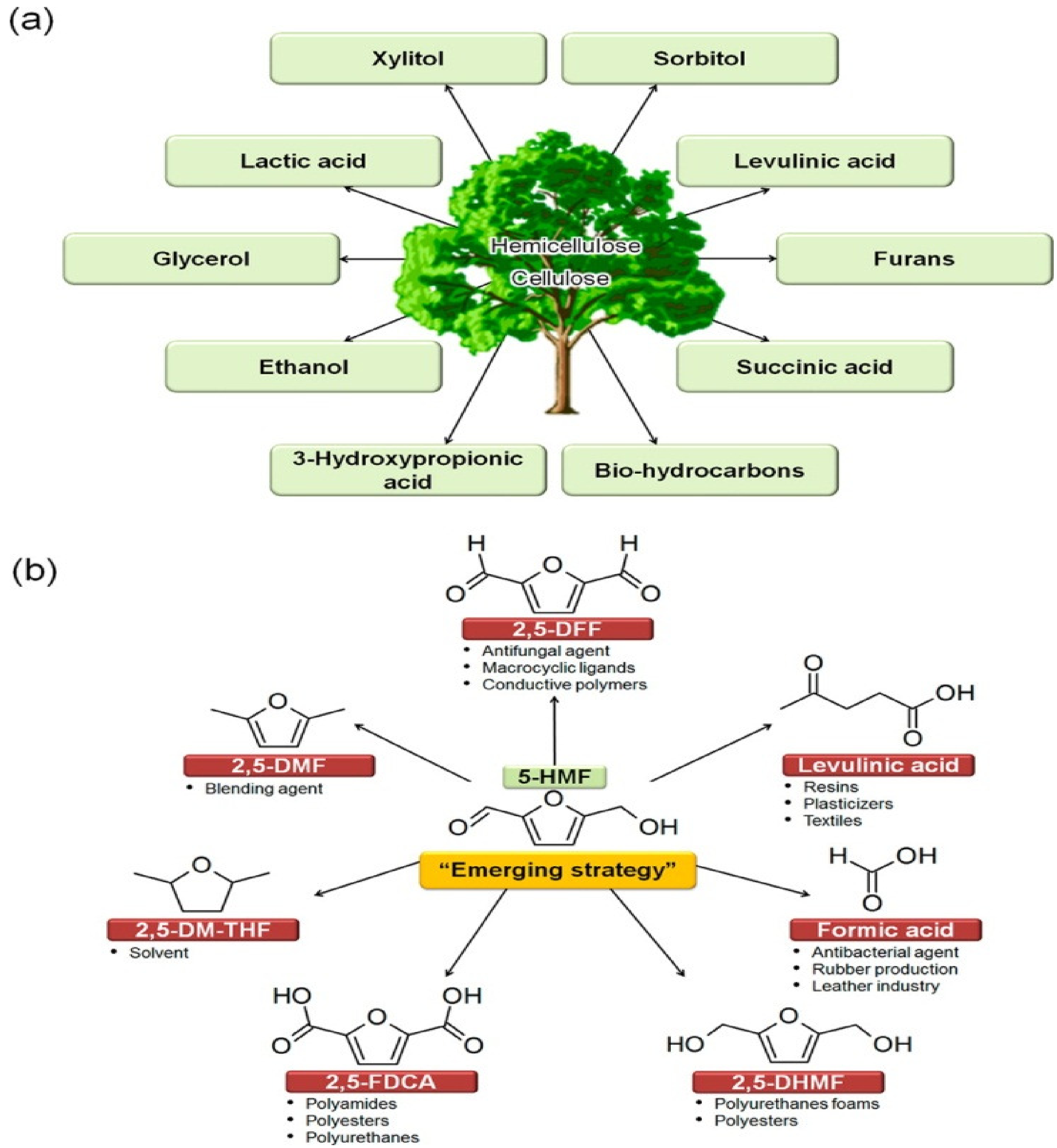
TERMINOLOGY

POLYMERS

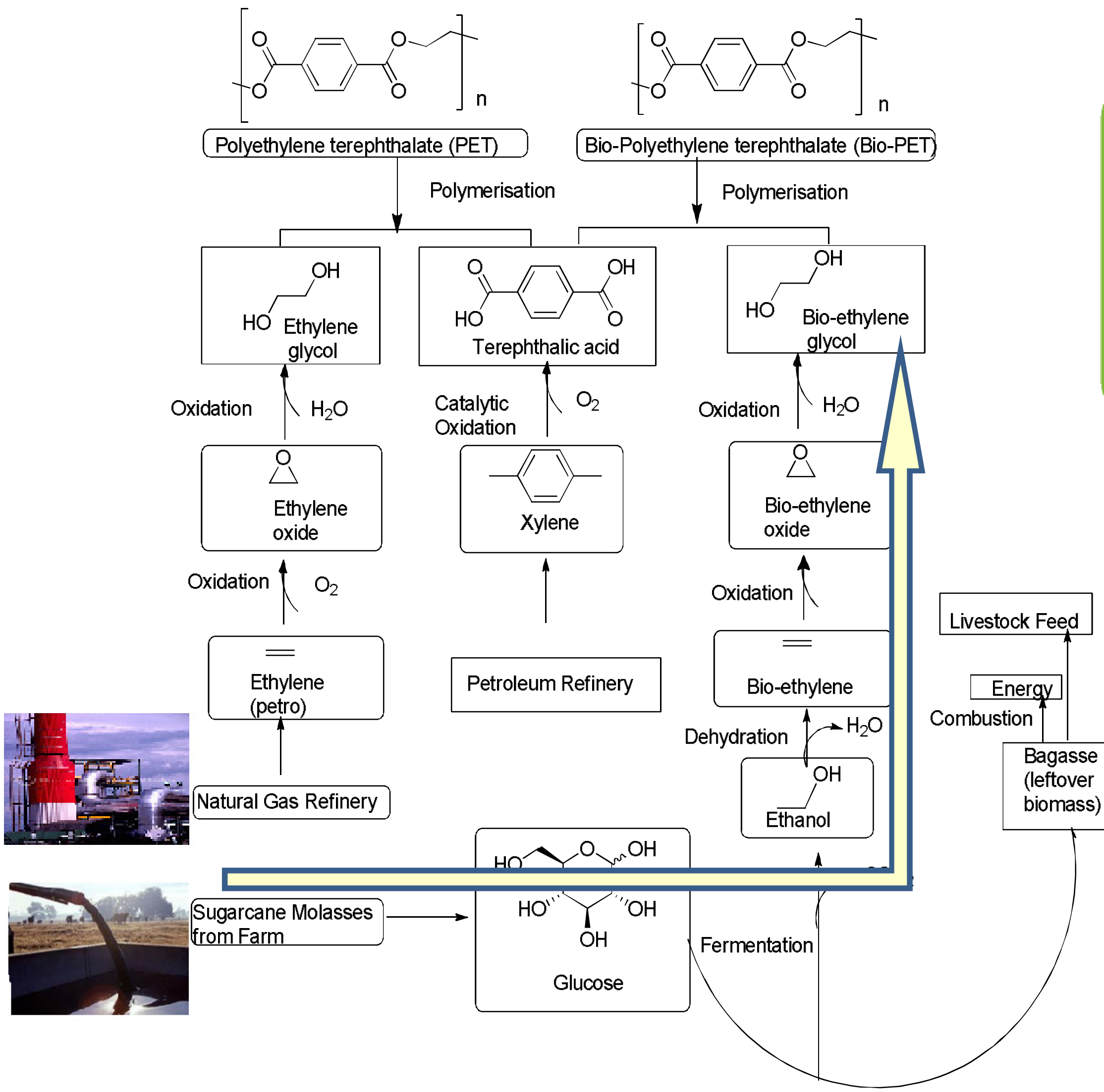
- DERIVED FROM FOSSIL FUEL
- BIO-BASED >25% RENEWABLE CARBON
- RENEWABLE 100% RENEWABLE CARBON
- DEGRAD-ABLE
- COMPOS-TABLE
- BIO-DEGRAD-ABLE


BIO-BASED POLYMERS
Directly extracted from biomass
Synthesised from bio-derived monomers
Produced directly by organisms
Polysachharides
Proteins
Lipids
Polylactate
PHA
Starch
Potato
Maize
Wheat
Rice
Derivatives
Animals
Plant
Crosslinked tri-glyceride
Other polyesters
Bacterial cellulose
Casein
Whey
Collagen
Gelantine
Zein
Soya
Gluten
Xanthan
Curdian
Pullan
Cellulose
Cotton
Wood
Other derivatives
Gums, Guar, Locust bean, Alignates, Carrageenan, Pectins, derivatives
Chitosan/ Chitin


POLYMERS FROM RENEWABLE RESOURCES
Biodegradable polymers
Bio-derived monomers and polymers
Polyesters
Starch
PET/PTT / PBS
Nylon-11
Ethylene from ethanol and polyethylene
•Environmental sustainability
•CO_2 mitigation – closing the carbon cycle
•Food Vs material
•Reduce cost of feedstock
•Reduce dependence on fossil fuel

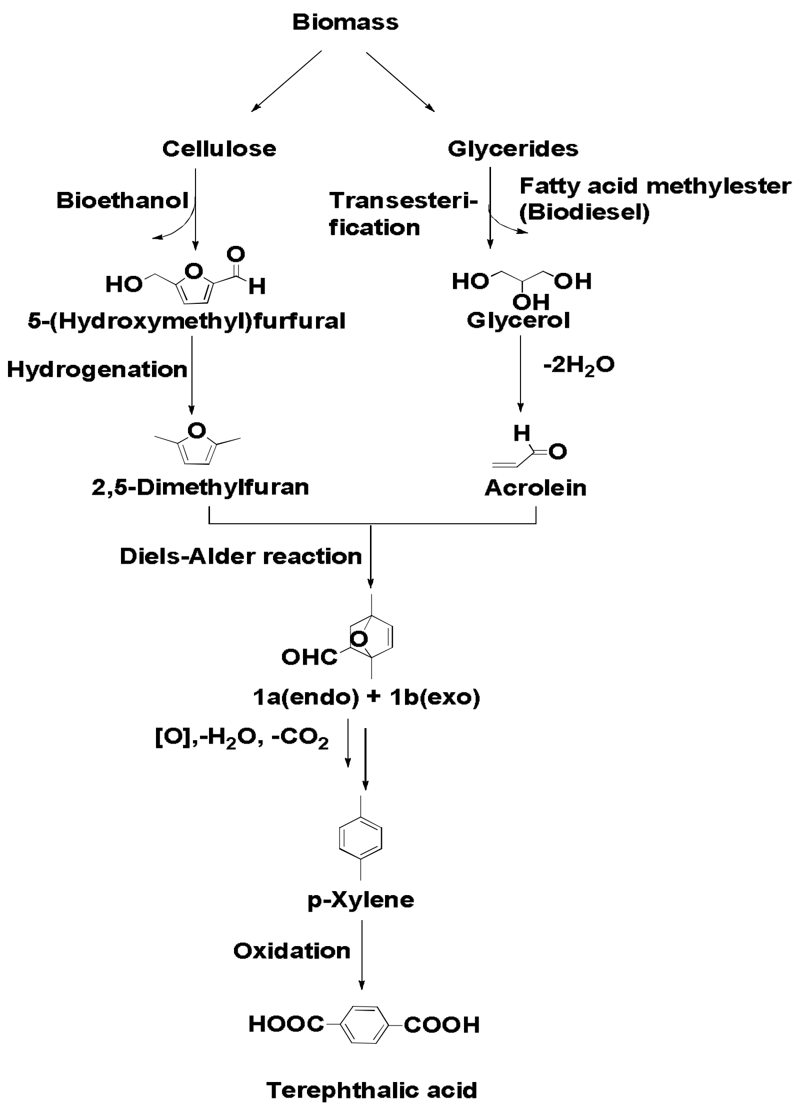

(a)
Xylitol
Sorbitol
Lactic acid
Levulinic acid
Glycerol
Hemicellulose
Cellulose
Furans
Ethanol
Succinic acid
3-Hydroxypropionic acid
Bio-hydrocarbons
(b)
2,5-DFF
Antifungal agent
Macrocyclic ligands
Conductive polymers
2,5-DMF
Blending agent
5-HMF
Levulinic acid
Resins
Plasticizers
Textiles
"Emerging strategy"
2,5-DM-THF
Solvent
Formic acid
Antibacterial agent
Rubber production
Leather industry
2,5-FDCA
Polyamides
Polyesters
Polyurethanes
2,5-DHMF
Polyurethanes foams
Polyesters

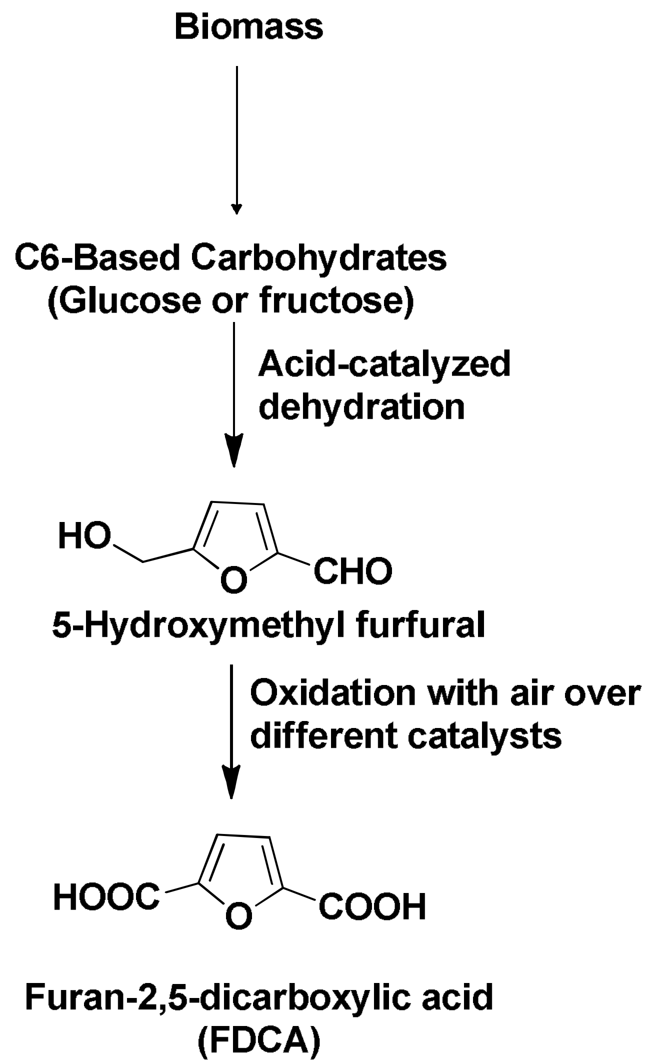
PET MANUFACTURE: PETRO- AND BIO-BASED



Adapted from Environ. Sci. Technol., 44, 8264 (2010)

BIOMASS DERIVED DICARBOXYLIC ACIDS FOR PET





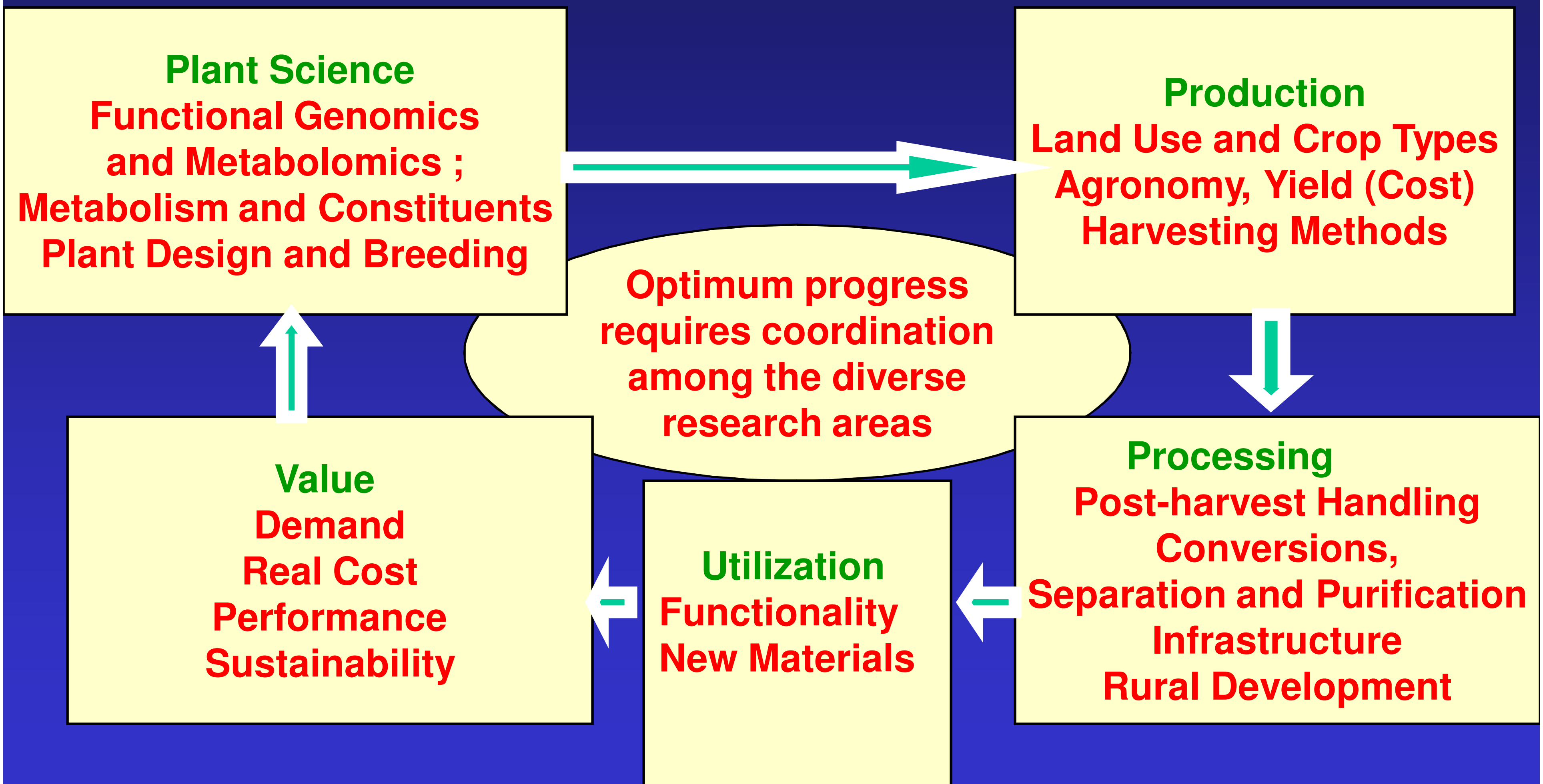
Irrespective of whether the bottles are made from fossil fuel or biomass, is the consumption sustainable ?

Every second we throw away about 1500 bottles

Over 30 billion liters of bottled water is consumed annually

Where does the solution lie ?

OPTIMIZATION OF RENEWABLE RESOURCE UTILIZATION



GRAND CHALLENGES IN BIOMASS PRODUCTION

- **Increase biomass yield by a factor of 2 from current global average of ~10 dry Mg ha^{-1} year^{-1}**
- **Accelerated domestication of perennial species as renewable feed stocks for conversion to fuels and materials**
- **Increase capture of light energy (rate of photosynthesis) by plants, which at present is <2% by genetic manipulation of plant enzyme that converts CO_2 to organic carbon**
- **Designing plants capable of withstanding drought and temperature stress**
- **Ability to decrease lignin content with a concomitant increase in cellulose by repressing lignin biosynthetic gene 4^{-}CL**
- **Down regulation of lignin biosynthetic gene CCR to alter plant cell wall structure, leading to more efficient enzymatic conversion of cellulose to sugars**

GRAND CHALLENGES IN BIOMASS CONVERSION

- **Efficient pretreatment processes**
- **Low cost microorganism capable of both cellulase production and ethanol fermentation at enhanced rates**
- **Genetically modified organisms (yeasts) capable of fermenting a mixture of hexoses and pentoses in high yields**
- **Understand and manipulate ethanol and sugar tolerance and resistance to potential inhibitors generated in pretreatment steps**
- **Understand the influence of variability of biomass resources**

BIO BASED MONOMERS FOR POLYMERS

Scientific Challenges

- ***Creating monomers from fossil fuel based feed-stocks is about selectively introducing functionality***
- ***Creating monomers from bio based feeds-tocks is about selectively removing functionality (examples, dehydration, decarboxylation, decarbonylation, deoxygenation)***

INTEGRATION OF DIVERSE COMPETENCIES

- DuPont and Tate and Lyle JV : proprietary fermentation process to produce Bio-PDO™ (1,3 propanediol) using corn sugar (40% less energy and 20% reduced GHG)
- Energy crop company Ceres, Inc : cellulosic path to acrylic monomer that has synergy with biofuel production
- Cargill and Novozymes, to develop technology for production of acrylic acid via 3-hydroxypropionic acid (3HPA) from renewable raw materials using a bioengineered microorganism
- Mazda Motor, collaboration with Teijin Limited and Teijin Fibers Limited, has developed a fabric made from plant-derived fibers, suitable for use in vehicle interiors
- Isobutanol (Gevo), hydrocarbons in the gasoline and diesel range from fatty acids (LS9,, Amyris) using modified bacteria produced by the tools of synthetic biology
- New enzymes and organisms that break down cellulose (synthetic bacteria) or better understanding the processes that occur in the guts of the cow or elephant (Mascoma , Verenium). The gut enzyme of a cow has 270 billion bases, 2million genes, of which 27, 000 genes belonges to an enzyme capable of breaking down polysaccharides (Science, 331, 463 (2011)

Company	*Technology*
OPX Biotech	Directed evolution technology platform for petro-based products(Acrylic Acid)
Lanza Tech	Modified clostridium to convert syngas to ethanol and 2,3-butanediol
Novomer	• Homogeneous catalyst for conversion of EO and CO to Propiolactone • Electrochemical conversion of carbon dioxide to CO on ceramic membranes • Conversion of EO and PO with carbon dioxide to Poly(alkylene) carbonate
Bioamber	Bioprocess for succinic acid
Geomatica	Bioprocess for I,4-butanediol
Zeachem	Bio-based packaging

Pro Bio	*Contra Bio*
Renewable resources conserve non-renewable fossil raw materials	**Competition with food production**
Lowering of carbon dioxide greenhouse gas emissions by switching from fossil fuels to biofuels	**Intensified farming, extensive use of fertilizers, deforestation, and grassland conversion cause drastic increases of greenhouse gas emissions**
Domestic energy supply and less dependence on oil imports	**Energy crop monocultures threaten biodiversity**
Plant cells and bacteria serve as solar microreactors for producing chemicals	**Use of transgenic plants and genetically modified bacteria**
Energy crops as nonfood incentives for farmers in industrialized countries with surplus food production	**Rising costs of food because farmers abandon food production in developing countries that are unable to feed their rapidly increasing population**
Use of agricultural and forestry wastes	**A portion of the biomass must remain on agricultural land to secure soil quality and natural habitats for animals**
Biodegradation	**No biodegradation in the absence of water and oxygen. Disintegration may cause nanoparticle emissions.**
No toxicity and no health hazards	**Spongy degrading biopolymer particles are food sources and breeding grounds for bacteria and spores, which could be inhaled.**

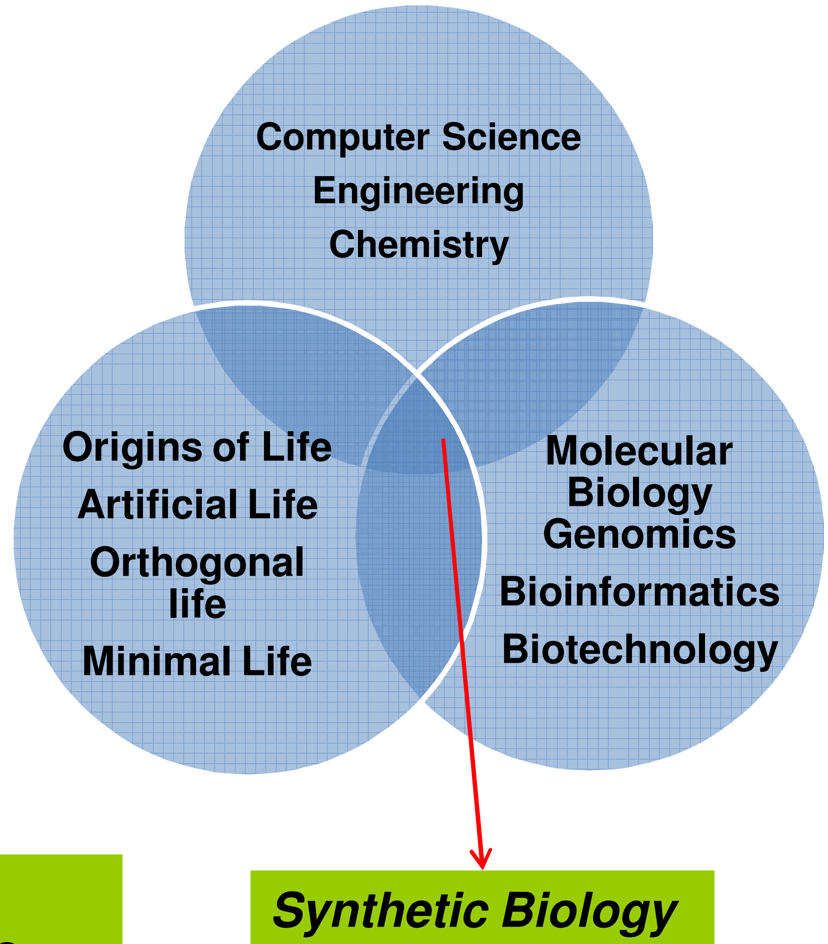
BIOLOGY TOOLS THAT ARE SHAPING THE FUTURE OF CHEMICAL INDUSTRY

- Plant molecular biology
- Genetic engineering
- Protein Engineering
- Genomics and metabolomics
- Industrial microbiology
- Catalytic thermophilic enzymes
- Bioreactor engineering and fermentation
- Directed Evolution to create adaptive organisms
- Metabolic pathway engineering
- Synthetic biology

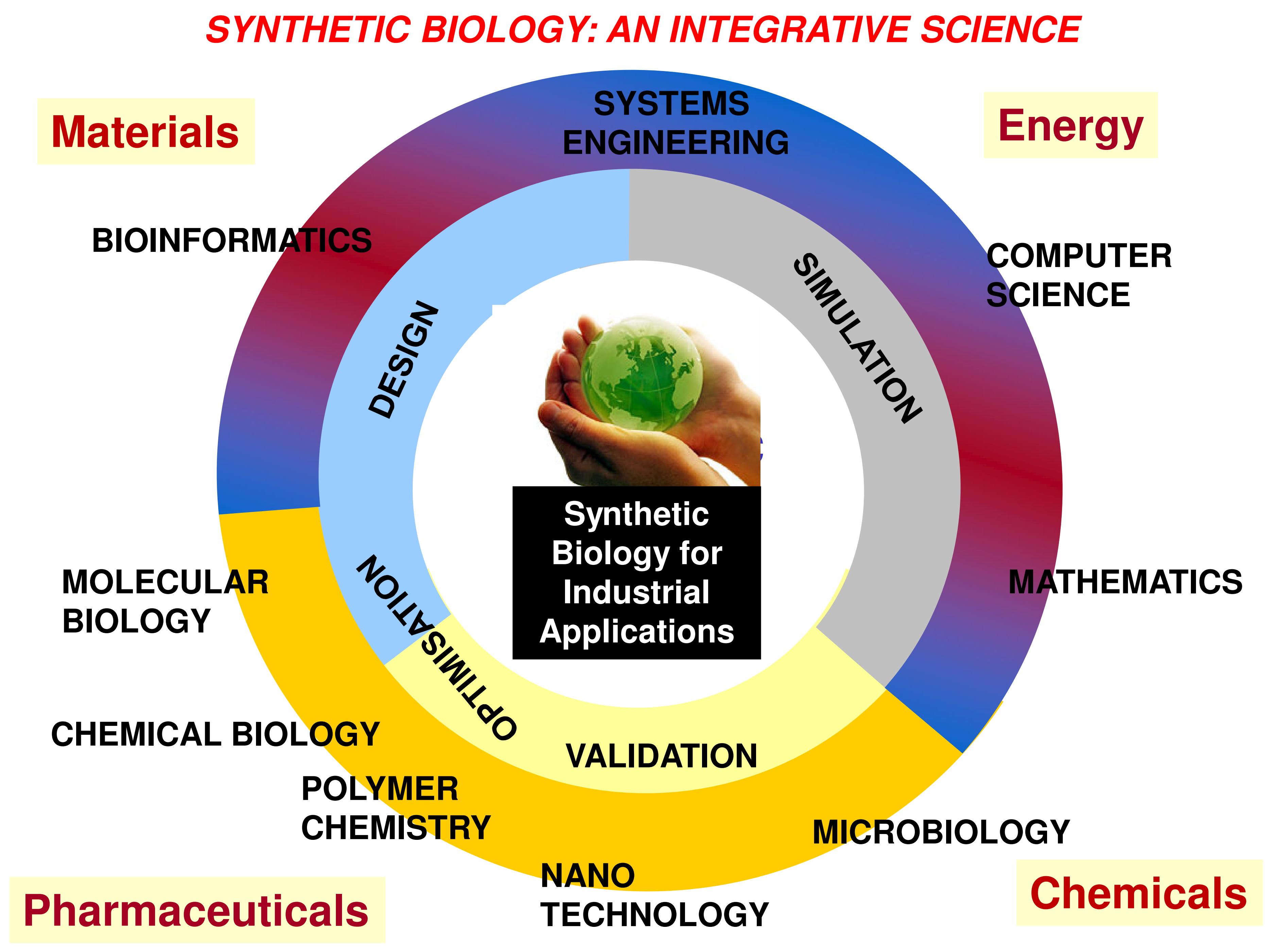
SYNTHETIC BIOLOGY: APPLYING ENGINEERING TO BIOLOGY

Synthetic biology is the engineering of biology; the synthesis of complex, biologically based (or inspired) systems which do not exist in nature. The engineering perspective may be applied to all levels of the hierarchy of biological structures- from individual molecules to whole cells, tissues and organisms

European Union , 2005



Objective
Engineering new biological pathways
Creating, de novo, new organisms


SYNTHETIC BIOLOGY: AN INTEGRATIVE SCIENCE
Materials
Energy
SYSTEMS ENGINEERING
BIOINFORMATICS
COMPUTER SCIENCE
DESIGN
SIMULATION
Synthetic Biology for Industrial Applications
MOLECULAR BIOLOGY
MATHEMATICS
OPTIMISATION
CHEMICAL BIOLOGY
VALIDATION
POLYMER CHEMISTRY
MICROBIOLOGY
NANO TECHNOLOGY
Pharmaceuticals
Chemicals

THE THIRD WAVE IN BIOTECHNOLOGY

- **First Wave : Food Security**
- **Second Wave : Health Security**
- **Third Wave : Energy and Resource Security**

From reading of a genetic code to writing it, from random selection to designed selection, from creating the gene to creating the chromosome


Resources are not scarce ; vision is
Reverence promotes repetition; Irreverence promotes innovation
The best way to predict the future is to create it


THANK YOU