MICROALGAE CULTIVATION FOR THE PRODUCTION OF RENEWABLE FUELS & HIGH-ADDED VALUE CHEMICALS

«*Algae:* The Energy Supplier of the Future»

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U.S. Consulate General in Thessaloniki

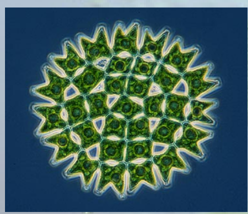
OUTLINE

- Introduction – Advantages of Microalgae.
- Microalgae Selection for Biomass Production.
- Potential Intermediate Products Derived from Microalgae Biomass.
- Microalgae-based Biorefinery Technology Platform.
- Microalgae Species Modification for Targeted Products.
- Microalgae Cultivation Systems.
- Microalgal Biomass Down-Stream Processing (Harvesting, Products Separation, etc.).
- Bio-fixation & Carbon Sequestration.
- Research Challenges - Important R&D Issues - Conclusions.

Microalgae (Introduction)

Algae (pl. n.) : any of various chiefly aquatic, eukaryotic, photosynthetic organisms, ranging in size from single-celled forms to the giant kelps.

Microalgae: are tiny (measured in micrometers), unicellular algae that normally grow in suspension within a body of water.



Macroalgae: are the large (measured in inches), multi-cellular algae often seen growing in ponds.

Algae "eat" CO_2, convert it to oil, proteins, carbohydrates and other useful products, and, emit only oxygen to the atmosphere.

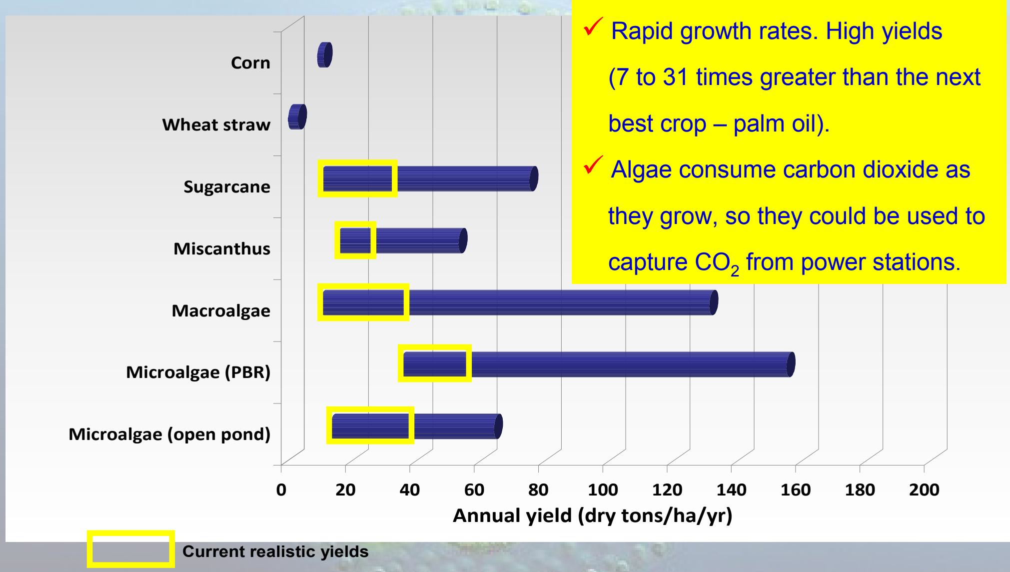
They are fast growing and efficient converter of solar energy capable of producing many times the biomass per unit area of land

Advantages of Microalgae

- ✓ High productivity-Rapid growth rates.
- ✓ Can be combined with nutrients removal from waste streams.
- ✓ High oil content.
- ✓ Marine water can be used (no fresh water use).
- ✓ No competition with food applications (use of marginal land.

- ✓ Low/neutral carbon footprint through biofixation of CO_2.
- ✓ Can produce valuable co-products.
- ✓ Economics improve as fossil fuel prices increase.
- ✓ Modular technology that can be scaled- up.

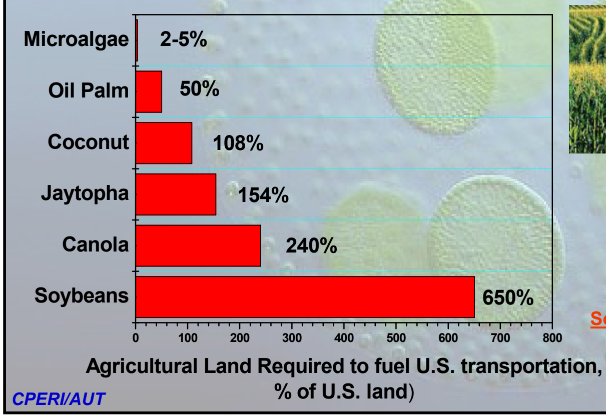
Why Microalgae ?



- ✓ Rapid growth rates. High yields (7 to 31 times greater than the next best crop – palm oil).
- ✓ Algae consume carbon dioxide as they grow, so they could be used to capture CO_2 from power stations.

Microalgae Energy Output Potential

	Corn ethanol	Algae biodiesel
Productivity (oil)	200-400 gal/ac/yr	2,000-5,000 gal/ac/yr
Productivity (energy)	17M-34M BTU/ac/yr	200M-600M BTU/ac/yr
Energy Production	84,000 BTU/gal	119,000 BTU/gal



Source: Biodiesel from Microalgae (Chisti, 2007)

Oil Content of Some Micro-Algae Species

Microalgae	Oil Content (% dry wt)
Botryococcus braunii	25-75
Chlorella sp.	28-32
Crypthecodinium cohnii	20
Cylindrotheca sp. (diatom)	16-37
Dunaliella primolecta	23
Isochrysis sp.	25-33
Monallanthus salina	>20
Nannochloris sp.	20-35
Nannochloropsis sp.	31-68
Neochloris oleoabundans	35-54
Nitzschia sp.	45-47
Phaeodactylum tricornutum	20-30
Schizochytrium sp.	50-77
Tetraselmis sueica	15-23

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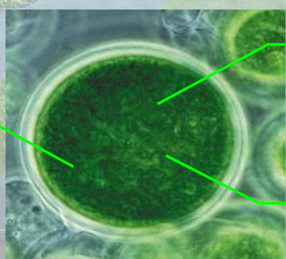
Microalgal Lipid Production Potential

Photosynthetic efficiency (%)	Lipids (%, dwt)	Algal Biomass (tons/ha/yr)	Algal lipids (bbl/ha/yr)
~ 6	50	33	118
~ 14	50	82	291
~ 20	50	123	441

Selected Species



$6CO_2 + 6H_2O \longrightarrow 6C_6H_{12}O_6 + 6O_2$

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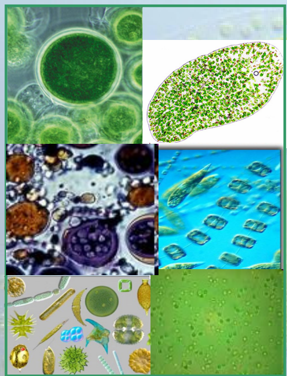
Biochemical Composition of Algae

Strain	Protein	Carbohydrates	Lipid	Nucleic acid
Scenedesmus obliquus	50-56	10-17	12-14	3-6
Scenedesmus quadricauda	47	-	1.9	-
Scenedesmus dimorphus	8-18	21-52	16-40	-
Chlamydomonas rheinhardii	48	17	21	-
Chlorella vulgaris	51-58	12-17	14-22	4-5
Chlorella pyrenoidosa	57	26	2	-
Spirogyra sp.	6-20	33-64	11-21	-
Dunalliela bioculata	49	4	8	-
Dunalliela salina	57	32	6	-
Euglena gracilis	39-61	14-18	14-20	-
Prymnesium parvum	28-45	25-33	22-39	1-2
Tetraselmis maculata	52	15	3	-
Porphyridium cruentum	28-39	40-57	9-14	-
Spirulina platensis	46-63	8-14	4-9	2-5
Spirulina maxima	60-71	13-16	6-7	3-4.5
Synechoccus sp.	63	15	11	5
Anabaena cylindrica	43-56	25-30	4-7	-

Microalgae Cultivation Requirements of Potential Products

CO_2

Nutrients (N,P….)



Source of fine chemicals & bioactive substances

- carotenoids / phycobiliproteins
- ω-3 & ω-6 fatty acids
- polysaccharides
- antioxidants
- bactericides, fungicides
- plant growth promotors

Feed / aquaculture

Proteins, PUFA, antioxidants

Soil conditioners / agrochemicals

Growth promotors, fungicides, polyssach.

Energy Carriers

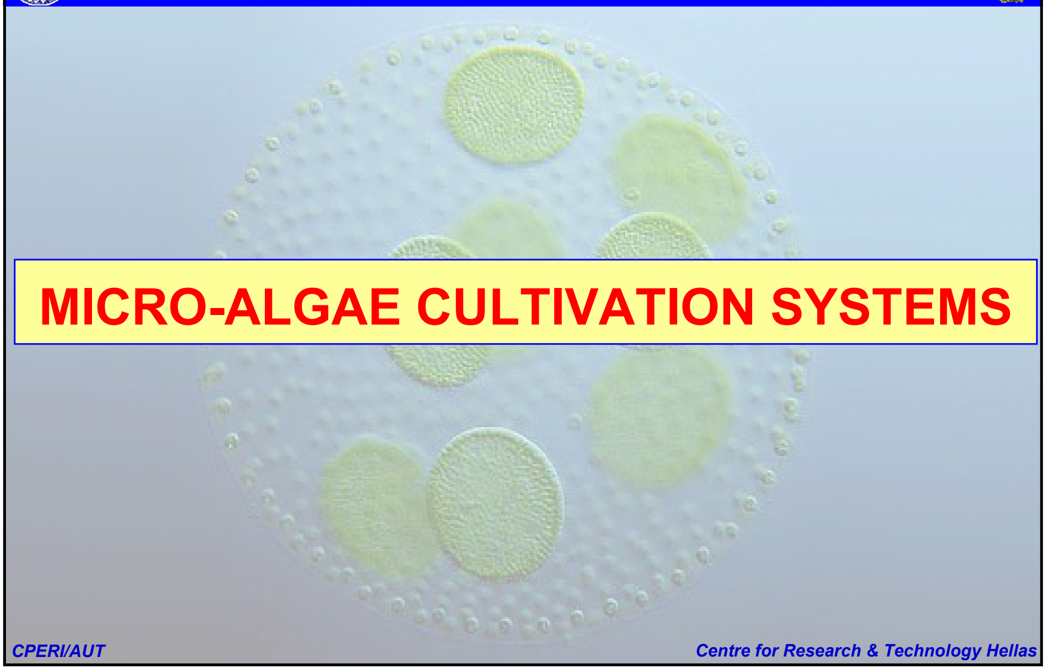
Biodiesel, hydrocarbons, methane, ethanol

What affects Algal Growth …

- Selected algal strain
- Light conditions
- Water salinity
- Supply of carbon dioxide (use exhaust gas of power plants)
- Macro-nutrients: C,N, P, Mg, Ca, K, Na, Cl
- Micro-nutrients (trace elements): Fe, B, Zn, Mn, Mo, Cu, SO_4, Co, Cd, Va, Al, Br, etc.

Some High & Low-Value Bioproducts Extracted from Algal

Chemical	Usage	Approx Value ($/kg)
Phycobiliproteins / Carotenoids	Medical diagnostics, Cosmetics, Pro-vitamins, Pigmentation	> 10.000
Poly-unsaturated fatty acids	Food addittives, nutraceutics	> 5.000
Xanthophyll	Fish feeds	~1.000
Beta-carotene	Food supplement	> 500
Whole-cell dietary supplements	Food supplement	> 50
Health supplements	Dietary supplements	~10
Biofuels	Energy	1.0 <
Phycoerythrin	Medical	15 $/mg
Pharmaceutical proteins	Pharmaceuticals	N/A
Vitamins	Nutrition	N/A



MICRO-ALGAE CULTIVATION SYSTEMS

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Microalgae Cultivation Systems

Possible Designs

✓ Open Systems

Advantages

- Simple/cheap to construct.
- Easier to operate & maintain.

Disadvantages

- Poor light utilization.
- Difficulty controlling light & temperature.
- Contamination & evaporation.

✓ Closed Systems

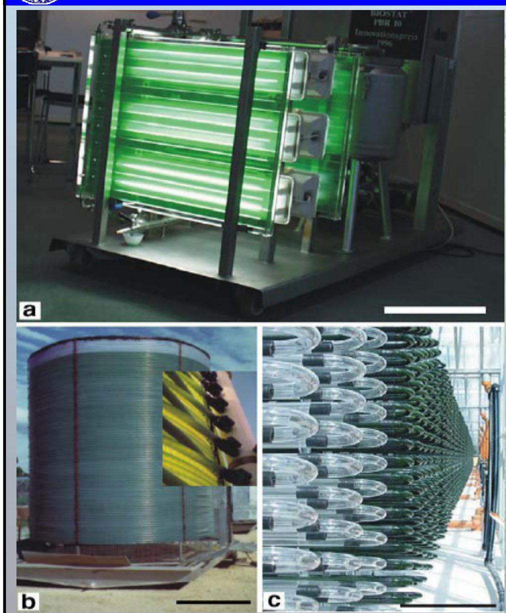
Advantages

- Higher productivity.
- Less contamination, water use & CO_2 losses.
- Better light utilization & mixing.

Disadvantages

- Cost/complex.
- Oxygen Accumulation.
- Biofouling.
- Cell damage by shear stress.

Photobioreactors Using Sunlight & Artificial Light



- ✓ Maximum use of light.
- ✓ Operate reactor at high intensity.
- ✓ Photo-inhibition at high light intensities.
- ✓ Supply of CO_2.
- ✓ Produced O_2 is toxic.

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Tubular Photobioreactors

Advantages

- ✓ Closed systems.
- ✓ Mixing via air and CO_2.
- ✓ Productivity 60tn/ha/yr.
- ✓ High surface to volume ratio.
- ✓ Biomass concentration 3 g/l.
- ✓ Scalable technology.
- ✓ Suitable for outdoor cultures

Disadvantages

- ✓ Gradients of pH.
- ✓ Dissolved O_2 and CO_2 along the tubes.
- ✓ Fouling.
- ✓ Some degree of wall growth.

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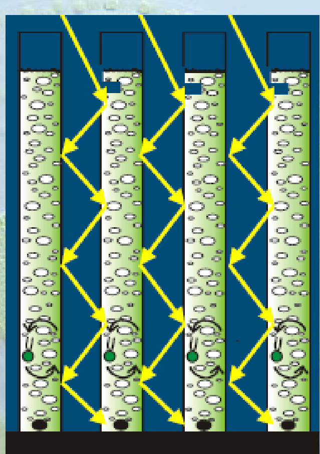
Tubular Reactor with Dilution of Light

General Characteristics

- ✓Tubular reactor
- ✓Efficient dilution of light.
- ✓Productivity 80 tn/ha/yr.



Bioprodukte – Produktions und Vertriebs GmbH

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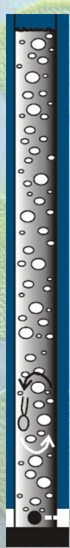
Flat Panel Reactor

General Characteristics

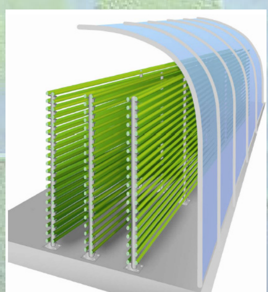
- ✓ Intensive mixing.
- ✓ Large illumination surface area.
- ✓ Efficient dilution of light.
- ✓ Good light path.
- ✓ Short light-dark periods.
- ✓ High biomass concentrations (>15 g/l).
- ✓ Productivity 100 tn/ha/yr.
- ✓ Easy to clean up.
- ✓ Low oxygen build up.
- ✓ Scalable ?

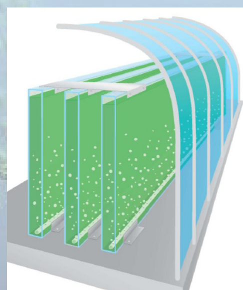


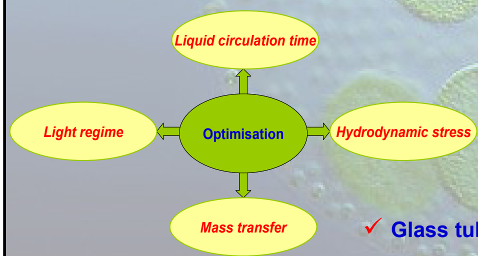
Microalgae Cultivation (Novel Designs)

- ✓ Algae production from power plant exhaust (Borne, 2007)

- ✓ Vertical algae reactor (Valcent Products, Inc El Paso, Texas, 2007)

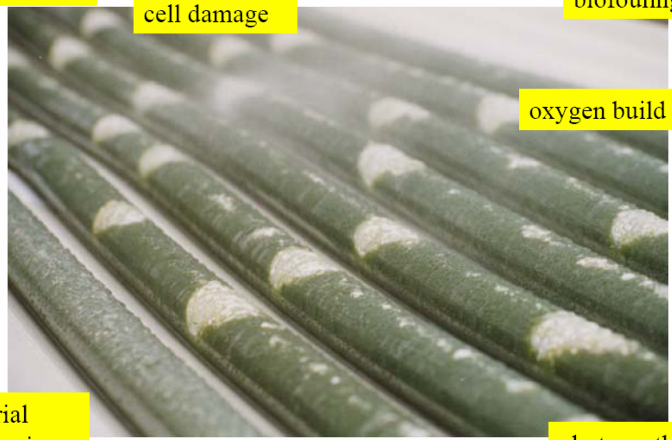






- ✓ Glass tube and plate photobioreactors (Solix Biofuels/ Colorado State University, 2008)

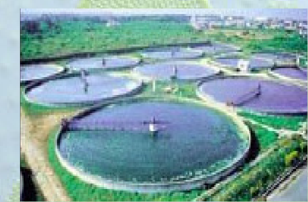
Closed Microalgae Cultivation Systems Limitations



Open Systems: Raceway Ponds

General Characteristics

- ✓ Mixing via paddle wheels.
- ✓ System that is used most.
- ✓ Low investments costs.
- ✓ Limitations in CO_2 supply.
- ✓ Productivity 20 tn/ha/yr.
- ✓ Biomass concentration < 0.5 g/l.
- ✓ High cost for harvesting.

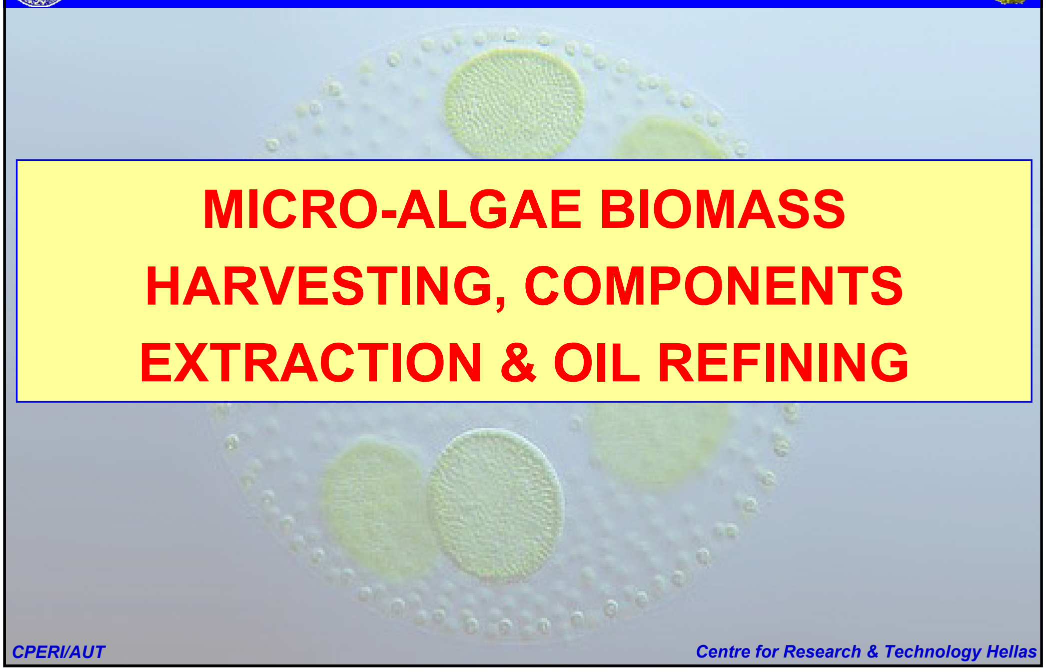


Typical Dimensions

- ✓ Depth 20 – 30 cm.
- ✓ Area 100 – 250 hectare.

Open vs Closed Microalgae Cultivation Systems

Characteristics	*Open Ponds*	*Photobioreactors*	Characteristics	*Open Ponds*	*Photobioreactors*
Land Requirements	High	Low	Waste Gas Use Capacity	Very Low	High
Biomass concentration	Low (0.1-0.5 g/L)	High (2-8 g/L)	Productivity Stability (Season, temp, sunlight, etc.)	Very Low	High
Contamination Risk	Very High	Very Low	Water loss	Very high	Low
Evaporation Losses	Very High	Very Low	CO_2 loss	High	Low
Staff Requirement	Very High	Very Low	Shear	Low	High
Maintenance Costs	Very Low	Very High	Biomass quality	Variable	Reproducible
Irreversible System Faults	Very High	Very Low	Production Flexibility	Few species possible, difficult to switch	High, switching possible
Microbial Safety	Very Low	Very High	Weather dependence	Very High	Low
Air Cleaning Capacity	Very Low	Very High	Startup period	8-10 weeks	2-4 weeks
Algal Species	Restricted	Flexible	Light Utilization Efficiency	Poor	Medium
Harvesting Efficiency	Low	High	Gas Transfer	Poor	High
Cultivation Period	Limited	Extended	Temperature Control	None	Very Good



MICRO-ALGAE BIOMASS HARVESTING, COMPONENTS EXTRACTION & OIL REFINING

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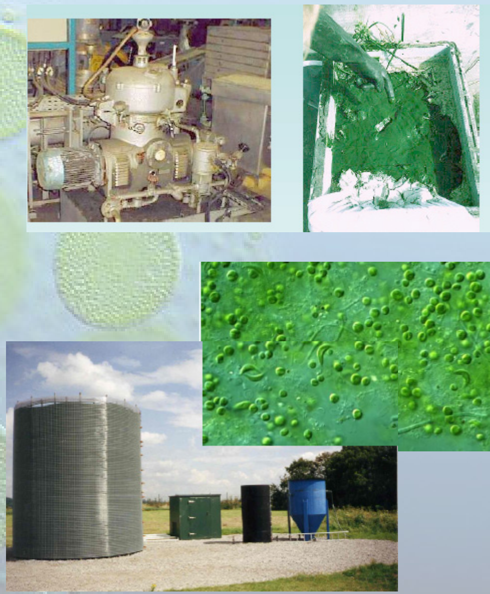
Microalgae Down Stream Processing: Harvesting (Cont.)

Traditional Approach

- ✓ Chemical flocculation.
- ✓ Centrifugation.
- ✓ Filtration.
- ✓ Dissolved air floatation.

Future Approach

- ✓ Bioflocculation.
- ✓ Micro-filtration.
- ✓ Enhanced Sedimentation.



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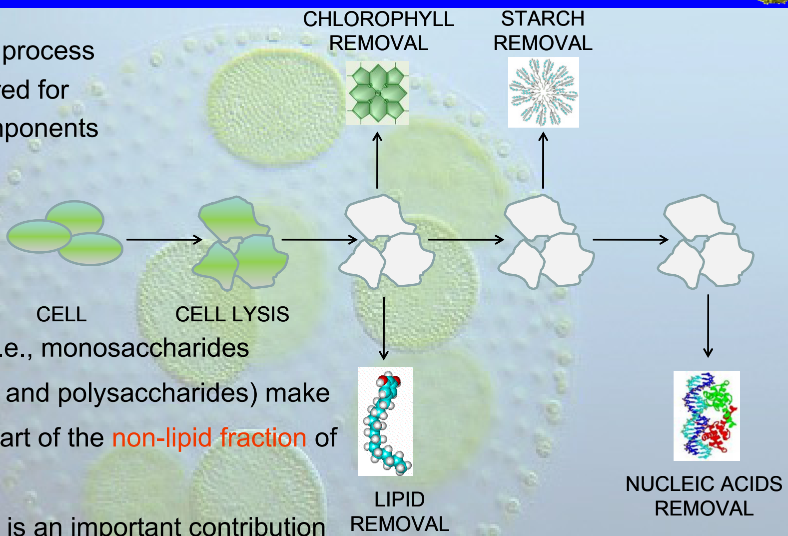
Microalgae Components Separation Process Steps

- ✓ A sequence of process steps are required for microalgae components separation.



- ✓ Carbohydrates (i.e., monosaccharides oligosaccharides and polysaccharides) make up a significant part of the non-lipid fraction of cell dry weight.
- ✓ These "leftovers" is an important contribution to the overall economics of an integrated microalgal-based technology.

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Conversion of Algal Oil to Biodiesel

Pressing Oil from the Algae

- Dry the algae and press the oil from it.
- Can retrieve up to 70% of the oil.
- While drying must prevent the algae from bevoming contaminated.
- Cheapest and simplest method.

Chemical Oil Extraction

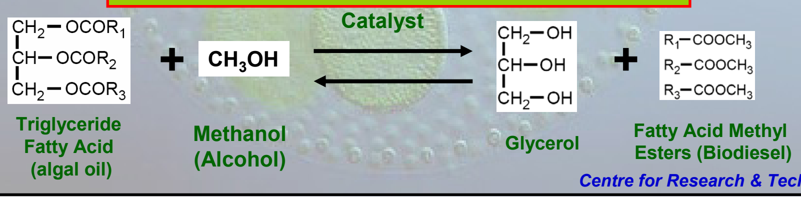
- Use hexane solvents to remove the oil.
- Hexane is a neurotoxin.
- Must be carefull when using.
- Removes oil out of almost all things.

Super Critical Oil Extraction

- Most efficient method.
- Uses CO_2 at critical pressure and temperature (CO_2 is almost liquid).
- Rapid diffusion of the oil.
- Very expensive method.

Various ways to produce biodiesel

- Base catalysed transterification with alcohol.
- Acid catalyzed esterification with methanol.
- Convert the oil to fatty acids, Then acid catalyze to alkyl esters.
- Enzymatic conversion of oil to biodiesel fuel.



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Microalgae Species Modification for Targeted Products

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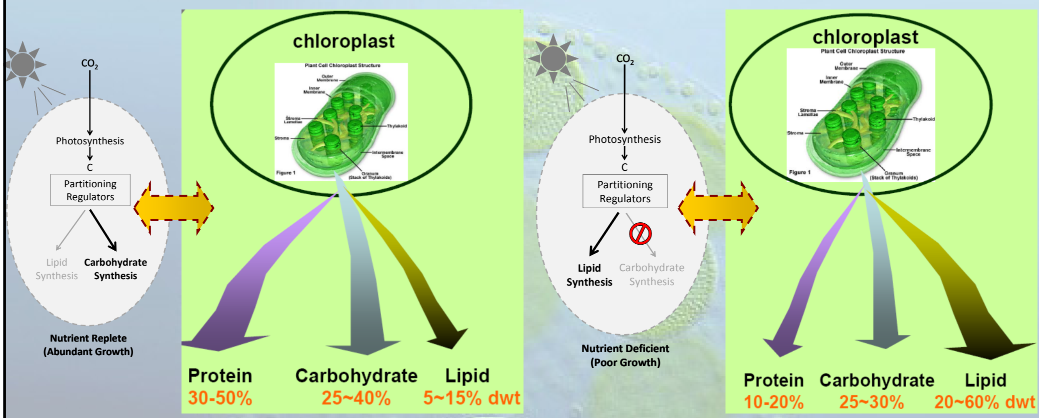
Identification of Pathway Regulation for Components Production

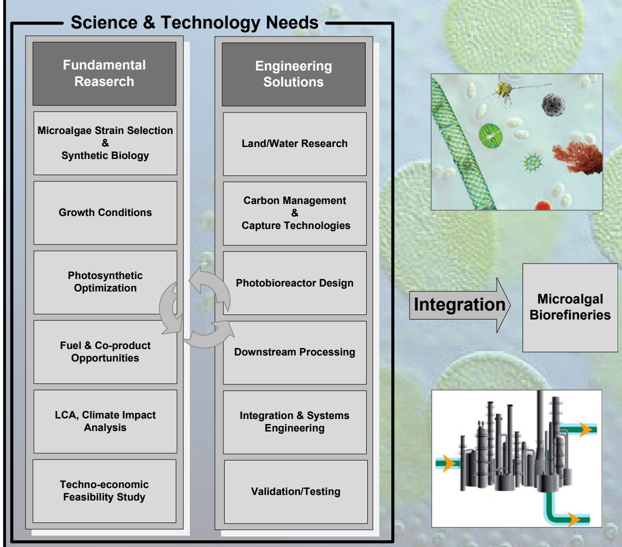


✓ If the metabolic path in the strain could be fully understood and controlled, it might be possible to manipulate either the culture conditions or/and the strains themselves to increase the accumulation of lipids or other components in a particular strain.

Microalgae-Based Biorefinery Technological Platform

Technological Platform for a Microalgae-Based Biorefinery

Technological Innovations & Breakthroughs



- ✓ An integrated microalgae-based processing concept offers many potential economic, environmental and security-related benefits to our society.
- ✓ It provides the option of co-producing high-added value, low-volume chemicals for niche markets together with the production of biofuels and energy that can offset the higher costs associated with processing of microalgal biomass materials.

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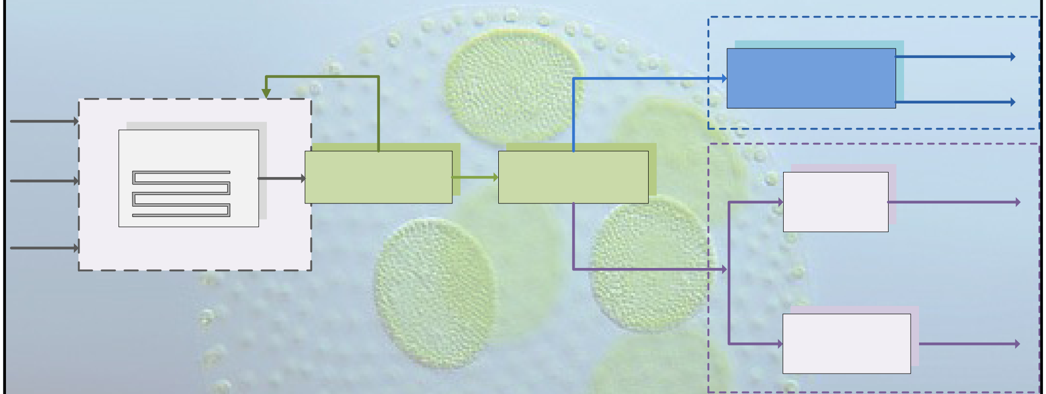
An Integrated Microalgal-based Processing Concept



(i) The "extracted bio-oil platform" for the production of biodiesel and high-added value bio-based chemicals (e.g., building blocks).

(ii) The "extracted microalgal biomass platform" for the production of renewable biofuels and fine chemicals

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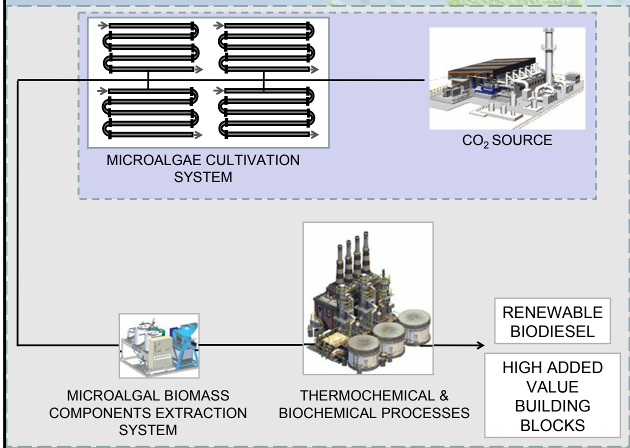
Integrated Biomass Production & Conversion Plant



An integrated microalgal biomass production and conversion process requires the combination of several systems:

a) Biomass cultivation system
b) Transport to conversion plants,
c) Product separation & recycling,
d) Processing,
e) Waste management,
f) Transport of saleable products and marketing.

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BIO-FIXATION & CARBON SEQUESTRATION

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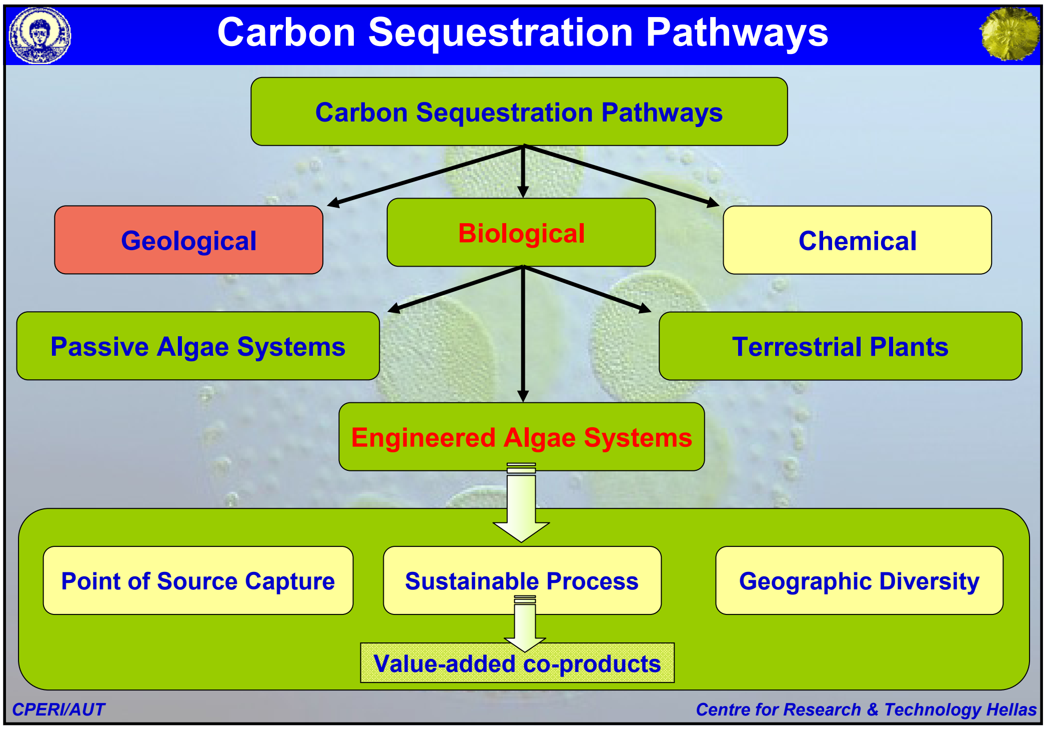
Carbon Sequestration Pathways
Carbon Sequestration Pathways
Geological
Biological
Chemical
Passive Algae Systems
Terrestrial Plants
Engineered Algae Systems
Point of Source Capture
Sustainable Process
Geographic Diversity
Value-added co-products
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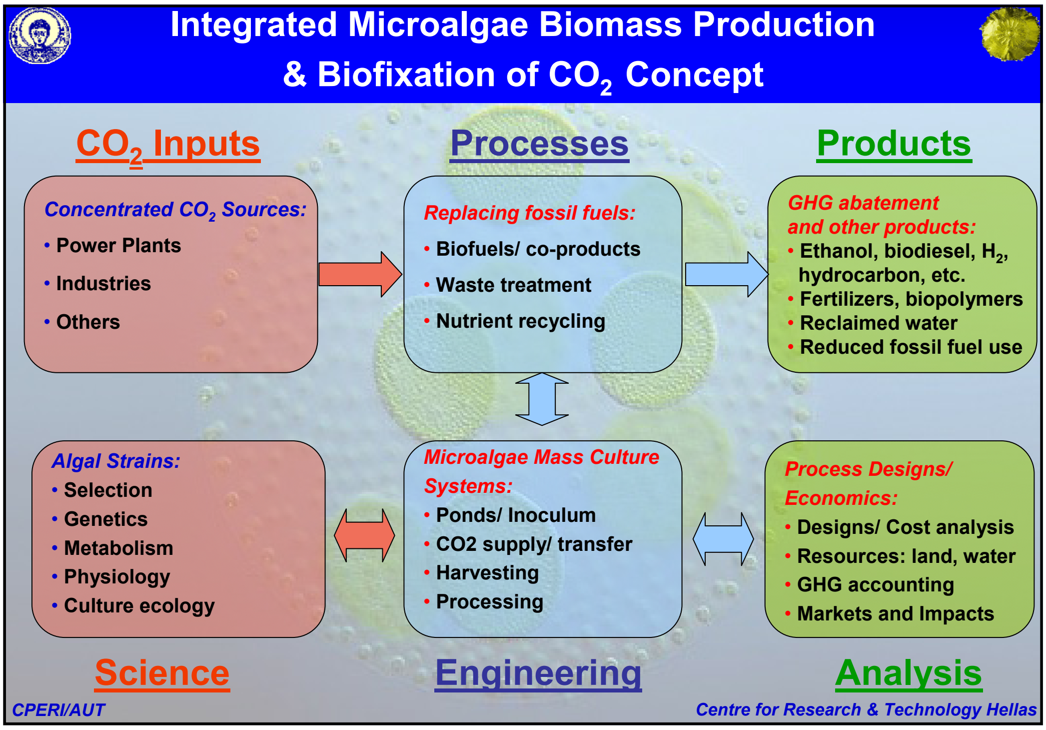
Integrated Microalgae Biomass Production
& Biofixation of CO_2 Concept
CO_2 Inputs
Processes
Products
Concentrated CO_2 Sources:
• Power Plants
• Industries
• Others
Replacing fossil fuels:
• Biofuels/ co-products
• Waste treatment
• Nutrient recycling
GHG abatement and other products:
• Ethanol, biodiesel, H_2, hydrocarbon, etc.
• Fertilizers, biopolymers
• Reclaimed water
• Reduced fossil fuel use
Algal Strains:
• Selection
• Genetics
• Metabolism
• Physiology
• Culture ecology
Microalgae Mass Culture Systems:
• Ponds/ Inoculum
• CO2 supply/ transfer
• Harvesting
• Processing
Process Designs/ Economics:
• Designs/ Cost analysis
• Resources: land, water
• GHG accounting
• Markets and Impacts
Science
Engineering
Analysis
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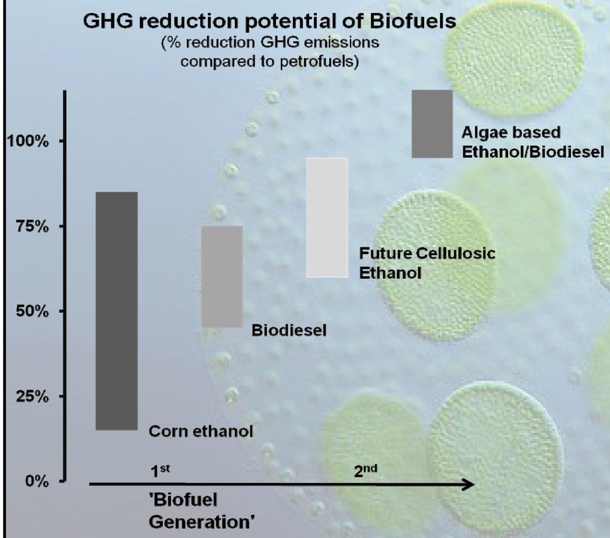
GHG Reduction Potential of Biofuels



- ✓ It is estimated that the bio-based products produced by an integrated microalgae-based processing plant have the potential to offset a larger amount of greenhouse gas emissions than that obtained from the lignocellulosic plants.
- ✓ Microalgae have been identified as fast growing species whose carbon fixing rates are higher than those of land-based plants by one order of magnitude.

TECHNOECONOMIC ASPECTS

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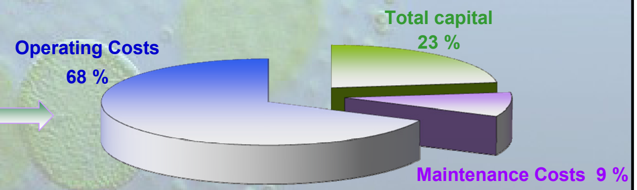
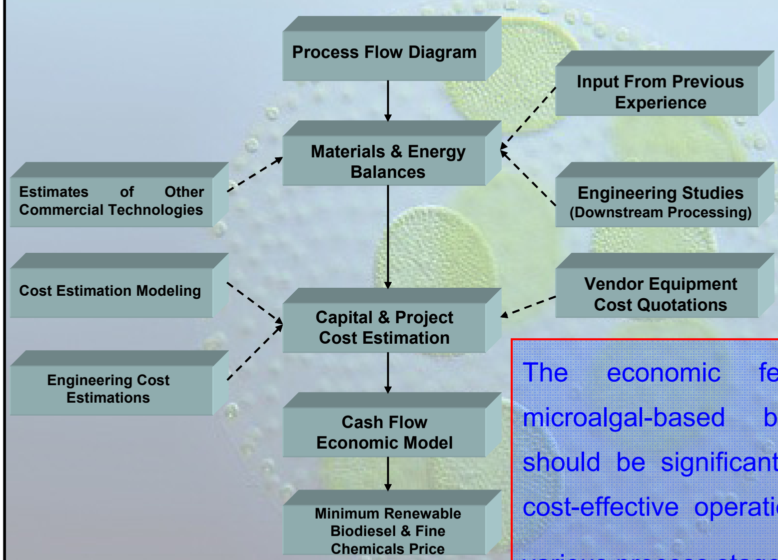
Parameters Affecting Microalgal Production Economy

Resource Parameters	Facility Design	Biology Parameter	Financial Parameter
❑ Evaporation ❑ Salinity of source water ❑ N_2, P, C in source water ❑ Land cost ❑ Energy cost ❑ Water cost ❑ Distance from CO_2 source ❑ CO_2 cost	❑ Effective culture area ❑ Effective culture downtime ❑ Design characteristics ❑ C, N losses ❑ Mixing velocity ❑ Mixing system efficiency ❑ Harvester solids removal ❑ Harvester type (microstrainer/cent-rifuge etc.)	❑ Ash, lipid, carbohydrates and protein content ❑ Salinity tolerance ❑ Phosphorus cell content ❑ Growing season and photsynthetic efficiency ❑ Density	❑ Return on debt ❑ Return on common stock ❑ Return on performed stock ❑ Cost escalation (inflation) ❑ Cover and linera cost

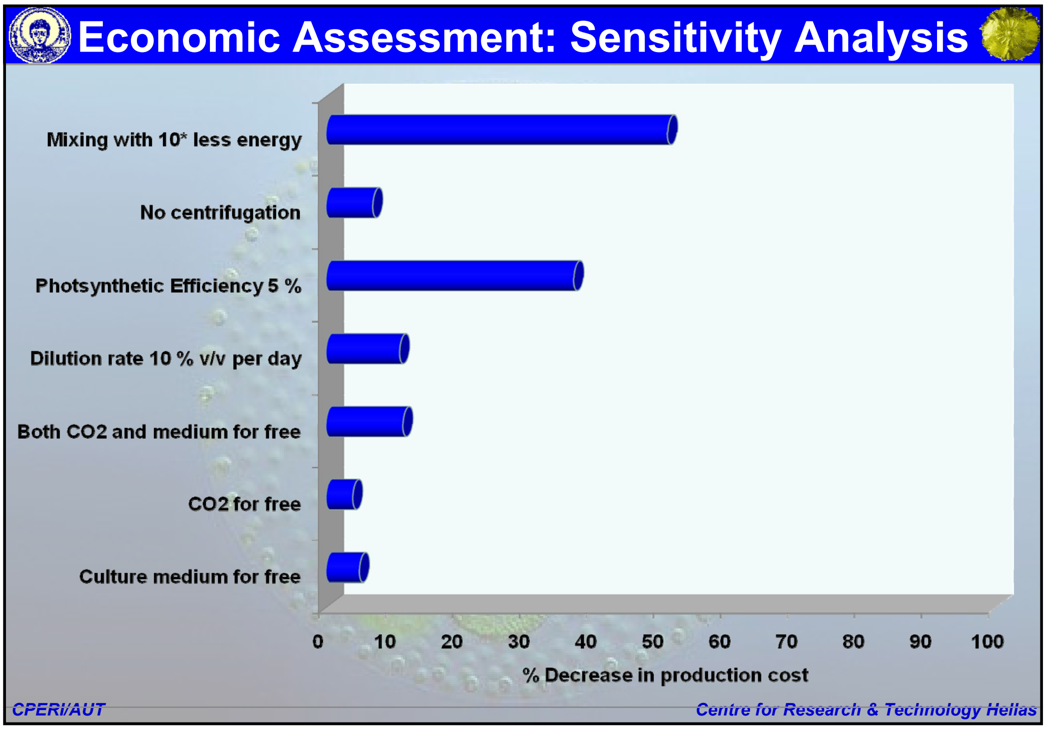
Product Cost Contributors by General Category



A Comprehensive Economic Assessment



The economic feasibility of the microalgal-based biofuel production should be significantly enhanced by a cost-effective operation strategy of the various process stages.


Economic Assessment: Sensitivity Analysis
Mixing with 10* less energy
No centrifugation
Photsynthetic Efficiency 5 %
Dilution rate 10 % v/v per day
Both CO2 and medium for free
CO2 for free
Culture medium for free
0 10 20 30 40 50 60 70 80 90 100
% Decrease in production cost
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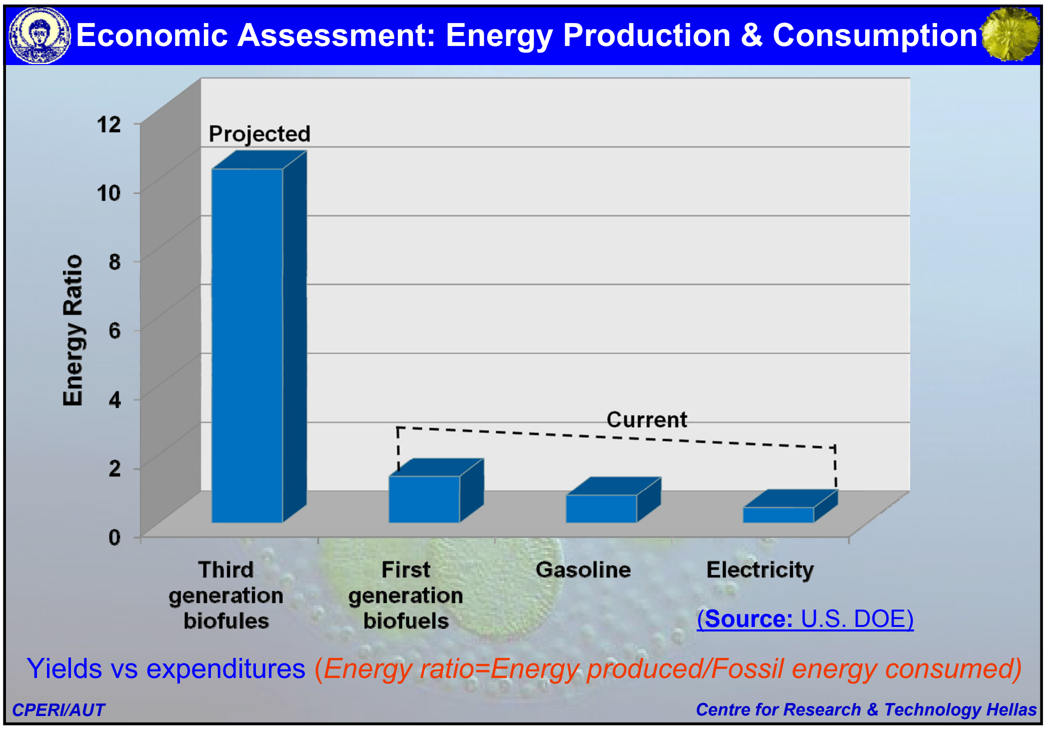
Economic Assessment: Energy Production & Consumption
Energy Ratio
0 2 4 6 8 10 12
Projected
Current
Third generation biofules
First generation biofuels
Gasoline
Electricity
(Source: U.S. DOE)
Yields vs expenditures (Energy ratio=Energy produced/Fossil energy consumed)
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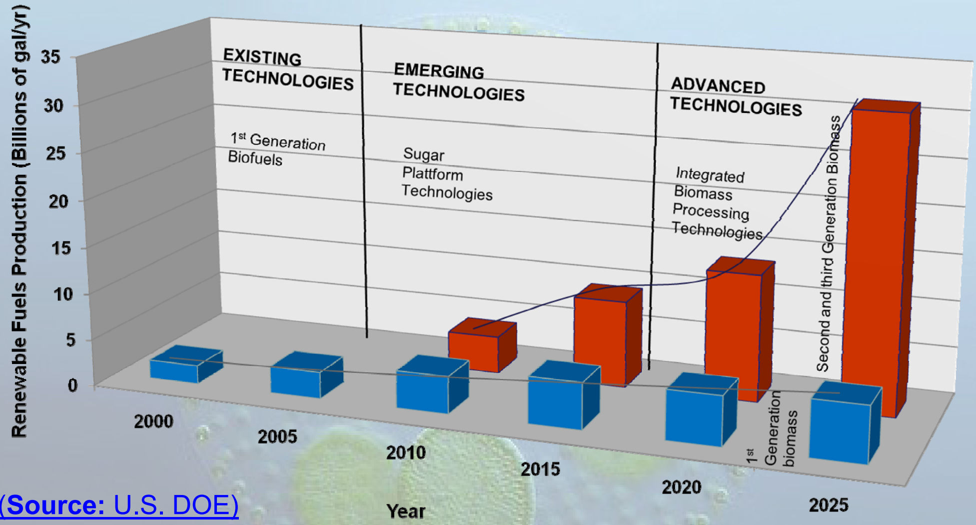
Global Production of Renewable Fuels



(Source: U.S. DOE)

It is clearly underlined the significant technological and economical potential associated with the integrated microalgal-based biomass biorefinery process.

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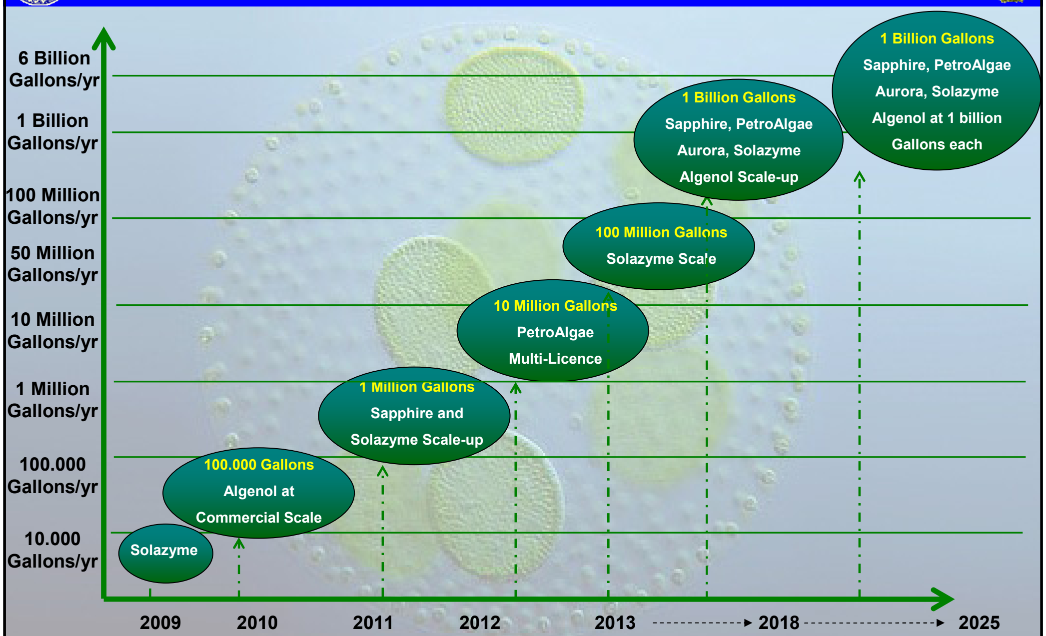
Algae Biofuels Forecast Scenarios



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Hot Research Areas/ Challenges

Algae Cultivation

Photobioreactor design
Capital and operating costs
Temperature control
Saline water chemistries
Makeup water (evaporation)
CO_2 availability and transport
Nutrient requirements
Starting species
Growth rate
Oil content & FA profile
Robustness
Resistance to invasion
Biofouling in closed systems
Nutrient induction requirement
Environmental impact

Intermediate Products Recovery

De-watering methods
Lipid extraction
Purification
Costs, energy input
Environmental issues
Value from residual biomass

Fuel Production

High Added Value Chemicals

Process optimization
Fatty acid profiles
Costs and LCA
Fuel characteristics
- Energy density
- Carbon numbers
- Cloud point
- Stability
- Consistency

Additives required
Engine testing
ASTM standard

Conclusions

- Microalgal route to biodiesel is a potential alternative to vegetable oil.
- Microalgal route to specialty biochemicals will ensure the technology sustainability.
- No competition with food production.
- Overall economics of the process needs improvement to be competitive substitute to petrochemically derived products.
- Roots of improvement in economy lie in both science and technology of microalgae.
- Extensive research on diverse aspects of cultivation systems is needed.
- Biorefinery approach can reassure the techno-economic feasibility and overall sustainability of a microalgae-based technology.


THANK YOU FOR YOUR ATTENTION
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