



# ***Next-Generation Biofuels: Cellulosic Ethanol and Algae-Based Biodiesel***

**Educational Materials  
December 2009**

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# *Cellulosic Ethanol*



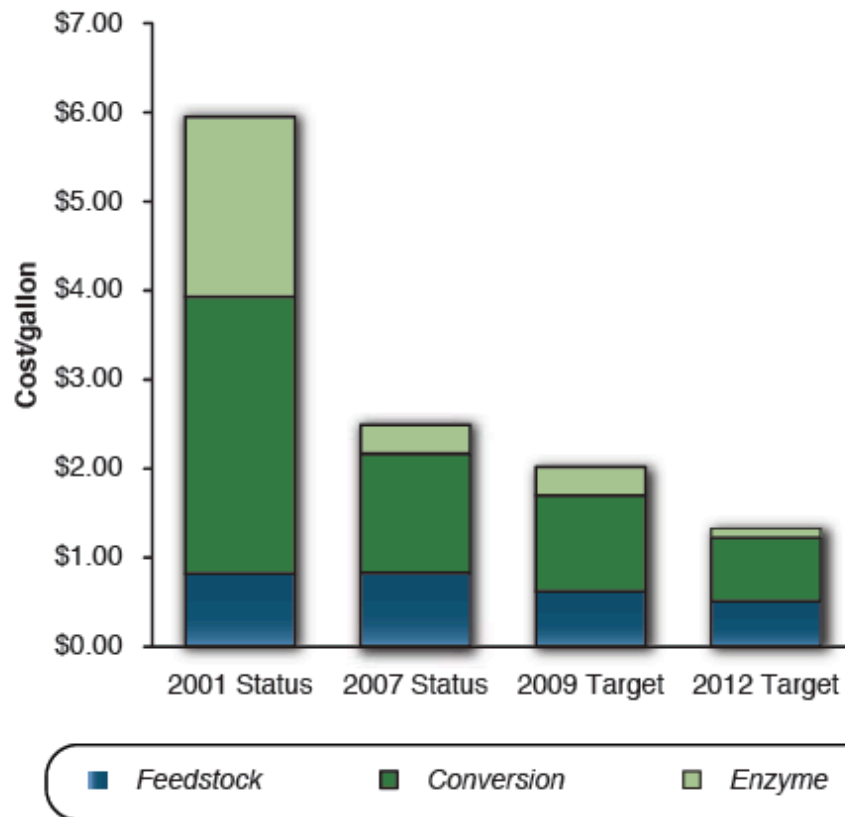
# ***Cellulosic Sources Requires Additional Processing To Become Ethanol***

- **Cellulosic materials must be broken down into intermediate sugars before fermentation**
- **“...one key barrier is the natural “recalcitrance” or resistance of plant fiber to break down into sugar intermediates.”**
  - **“National Biofuels Action Plan,” DoE, 10/08**



# Cellulosic Fuel Production Gets Cheaper Every Year

Figure 4: 2012 cost competitive target and status (biochemical)



Source: DOE EERE Office of the Biomass Program, Multi-year Program Plan, Appendix C.



Algae

# ***There Are Three Important Things to Understand About Algae Biofuels***

- **There is a market for renewable, sustainable, scalable and economical biofuels**
- **Algae can potentially meet these demands while avoiding moral dilemmas**
  - **Food**
  - **Freshwater**
  - **Farmland**
- **Algae biofuels should work in principle, but prove to be rather difficult to put in practice**



# ***The Potential Market for Algae is Quite Large***

- **Existing US Market for transportation fuels [2005]**
  - 135 Bgal/yr of gasoline
  - 40 Bgal/yr of diesel
  - 25 Bgal/yr of jet fuel
- **EISA 2007**
  - 0.5-1.0 Bgal/yr for advanced biodiesel by 2012
  - 5 Bgal/yr are undetermined...algae?
  - §228. ALGAL BIOMASS
- **USAF goal:**
  - 0.5 Bgal/yr of domestic jet fuel by 2016



# ***Why is there hype about algae and should we believe it?***

## **Strong Claims:**

- **Small fresh water requirements**      “Up to 6,000 gal/acre/yr!”  
- Waltz, Nature 2007
- **Small land requirements**
- **“Ultrahigh” biomass productivity**
- **High lipid yields**      “A real algae orgy” – Glen Kertz  
- Walton, cnn.com, 2008

## **Challenges:**

- **Evaluating the potential consistently**
- **The whole story – economics, energy, and materials**
- **Tools to assess and report claims**



“Between 1 and 3% of the total U.S. cropping area would be sufficient for ... 50% of the transport fuel needs”  
- Chisti, Biotechnology Advances, 2007



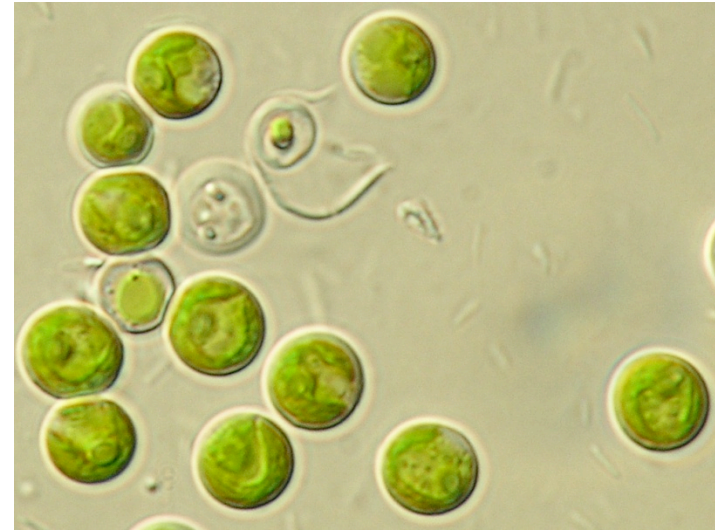
# ***Algae Are An Appealing Source of Next-Generation Biofuels and Chemicals***

- **Proteins**
  - **Nutrients for livestock**
- **Carbohydrates**
  - **Fermented to create ethanol**
- **Lipids**
  - **Triglycerides (TAGs): refined into biodiesel, synthetic diesel and gasoline, jet fuel, syngas and more**
  - **Bio-crude**



# ***Algae are simple, uni-cellular organisms***

- **Simple growth requirements**
  - **Sunlight**
  - **CO<sub>2</sub>**
  - **Water**
- **Carbon, nitrogen and phosphorous are assimilated during photosynthesis**



Chlorella vulgaris, <http://botany.natur.cuni.cz/algo/images/determin/chlvulgaris.jpg>



Images courtesy of Dr. Jerry Brand

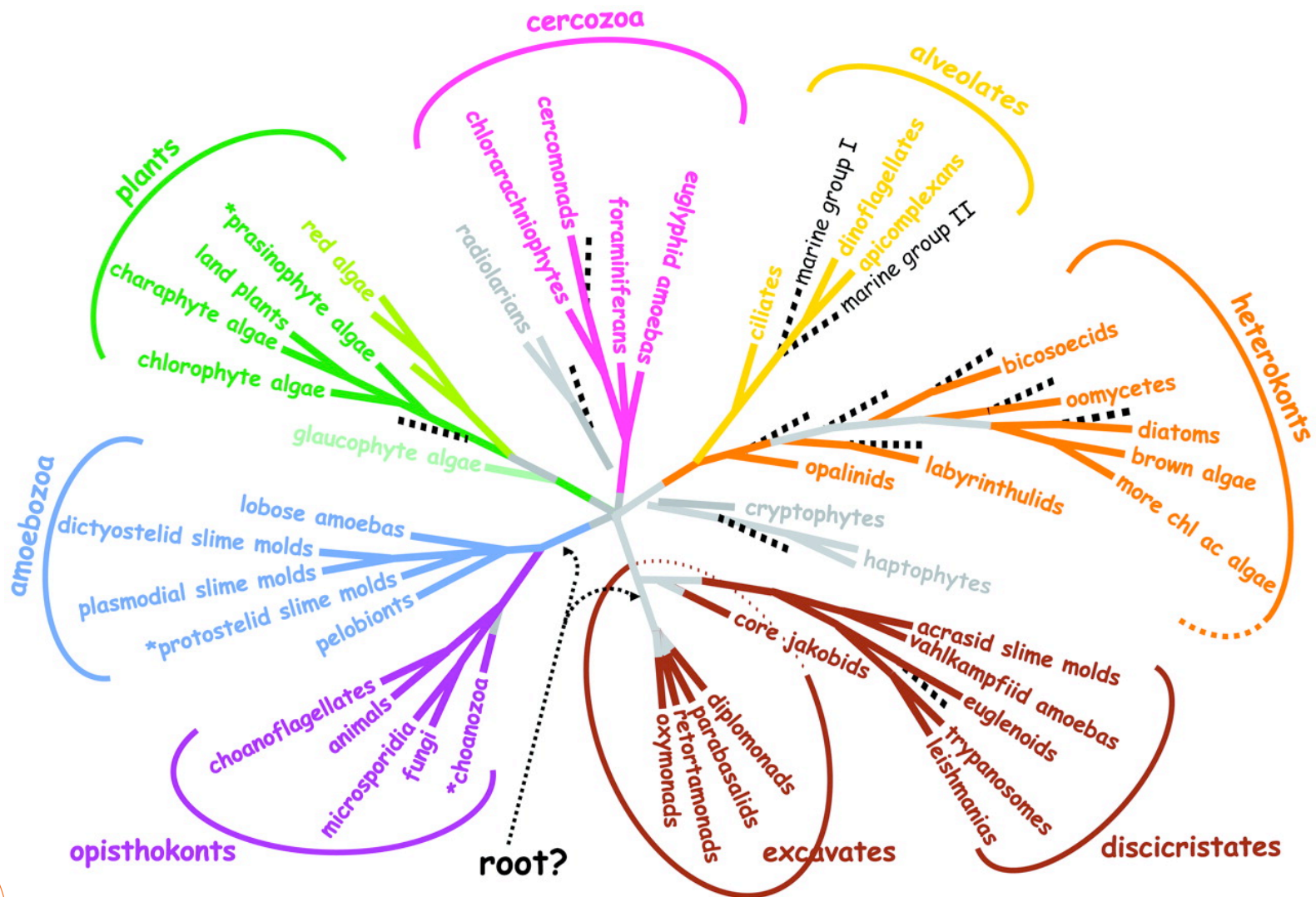


# ***Algae Are Very Diverse***

- **Algae are not easily categorized as a group of organisms**
  - **As a group, they are more diverse genetically than animals and are different than plants**
- **They are grouped together because of their common mode of nutrition**
  - **Phototrophic and perform oxygenic photosynthesis**
  - **Contain chlorophyll**



# Algae Are Present In Many Kingdoms...





# *Good News/Bad News: Algae Grows Whether You Want It To or Not*



# *Algae Is Grown Commercially Today*

- **Nutritional products**
  - **Spirulina**
  - **Health Supplements**
  - **Cosmetics**
  - **Food additive (bonding)**
- **Aquaculture**
- **Nori (sushi)**
- **Kim (Korea)**



# ***Algae Are Responsible for Much of the Earth Around Us***

- **Oceans full of prehistoric algae filled our atmosphere with oxygen**
  - **Assimilated CO<sub>2</sub> in the process**
- **Layers of compressed algae resulted in soil and limestone formations**
  - **i.e., Central Texas Hill Country**
- **Current petroleum deposits are, in part, old, decayed algae**



# ***Algae Contain A Varying Amount Of Lipids***

## ***Caution: Results Are Difficult to Interpret***

- **0-77% by dry weight**

<b>Microalga</b>	<b>Lipid content (% dry weight)</b>
<i>Botryococcus braunii</i>	25 – 75
<i>Chlorella sp.</i>	28 – 32
<i>Cylindrotheca sp.</i>	16 – 37
<i>Isochrysis sp.</i>	25 – 33
<i>Nannochloropsis sp.</i>	31 – 68
<i>Schizochytrium sp.</i>	50 – 77
<i>Tetraselmis sueica</i>	15 - 23

Adapted from Chisti, 2007





# ***Algae Have the Potential To Produce Large Quantities of “Oils”***

<b>Crop</b>	<b>Yield (gallons/acre-yr)</b>
Corn	18/300-400*
Cotton	35
Soybean	48
Jatropha	202
Oil Palm	635
Algae	2,000-20,000

NREL, Algal Biomass Summit 2007

\*gallons of ethanol



# ***Typical Algae Yields and Resource Consumption***

- **1 ton of algae biomass consumes:**
  - **1.83 tons of CO<sub>2</sub>**
- **1 ton of algae biomass yields:**
  - **~ 72 gallons of lipids**
  - **~ 18 gallons of biodiesel\***
- **1 ton of CO<sub>2</sub> yields:**
  - **~ 40 gallons of lipids**
  - **~ 10 gallons of biodiesel\***

\*assuming an arbitrary 50% volumetric processing efficiency



# ***NREL Aquatic Species Program Studied Algae Growth In The Desert Southwest For 18 years***

- **NREL Aquatic Species Program**
  - **1978 to 1996**
  - **Aimed to develop renewable transportation fuels from algae**
  - **Concerned with finding algal strains that produce high quantities of oil**
  - **Investigated growth under severe conditions**
  - **At one point contained 3,000 species**
    - **Winnowed to 300 species**
- **Discontinued due to budget constraints and cheap oil**



# ***Aquatic Species Program Demonstrated Open Pond Systems for Mass Production of Algae***

- **Large-scale open ponds were constructed**
  - **California, Hawaii, New Mexico**
  - **1,000 m<sup>2</sup> ponds built in Roswell, NM**
- **Tests showed that outdoor ponds could be run efficiently with high CO<sub>2</sub> utilization**
  - **Growth rates up to 50 gm<sup>-2</sup>d<sup>-1</sup> were achieved**
  - **15 gm<sup>-2</sup>d<sup>-1</sup> were typical**

**Note: gm<sup>-2</sup>d<sup>-1</sup> = grams per square meter per day**



# ***ASP Close-Out Reports Concluded High Cost of Algae Production an Obstacle***

- **Biological factors influence the cost of large-scale algae production**
  - **Cost of large-scale, high throughput oil extraction**
  - **Problems growing algae with high oil content reliably**



# ***High oil prices and environmental concerns have renewed interest in algae***

- **After a decade, interest algae-based fuels has renewed**
- **DOE had an R&D roadmapping workshop in December 2008**
  - **Is setting aside \$50M to resuscitate the program**
  - **a decade of valuable research has been lost**



# ***Growing Algae On A Large-Scale And Obtaining Useful Products Is Difficult***

- **Algal strains are diverse**
- **Algae outputs depend on**
  - **Growth conditions**
  - **Stresses and strains**
  - **Environment**
  - **Nutrients**
- **Fast growth rates vs. high lipid production**
  - **Algae produce lipids when they are dying**
  - **Lipids are an energy storage product**



# Algae Can Be Paired With Power Plants and Wastewater Treatment Plants

- Utilize CO<sub>2</sub> from flue gas
  - 12-14% CO<sub>2</sub>
  - Ideal concentration for algae growth
- Wastewater contains valuable nutrients
  - Nitrogen
  - Water

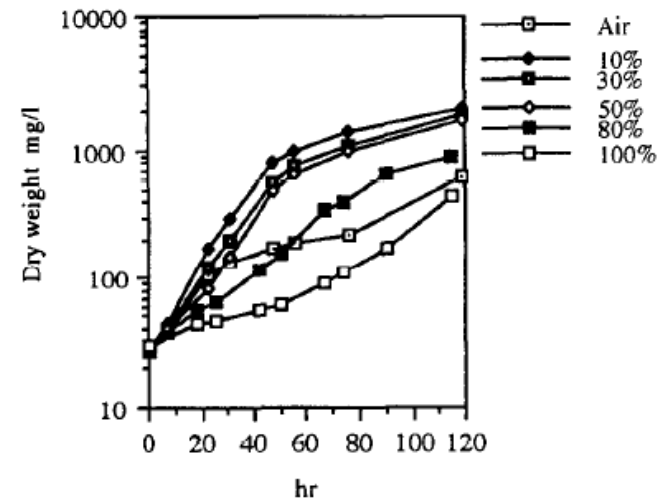


Fig. 2 Growth at different CO<sub>2</sub> concentration

Maeda, et al., 1995

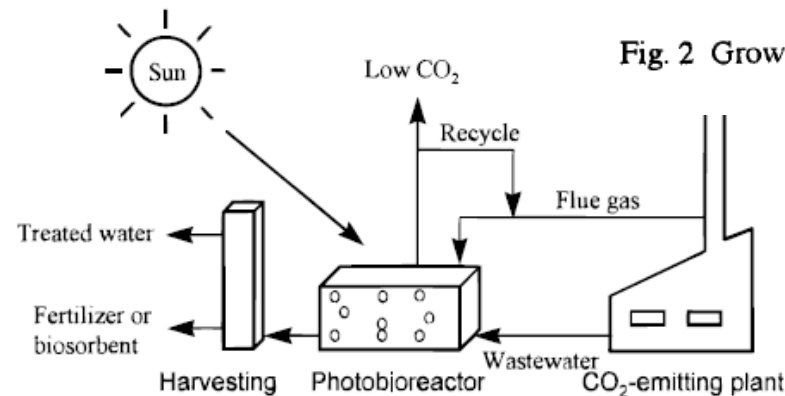


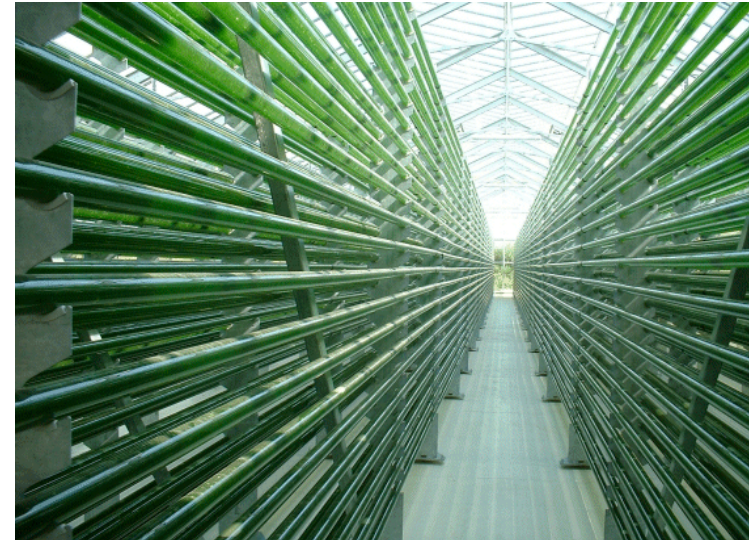
Fig. 1. Conceptual system of carbon dioxide fixation using wastewater nutrients discharged from a site of CO<sub>2</sub>-emitting plant.

Yun, et al., 1997





# Algae Can Be Grown In Ponds or Photobioreactors



<http://www.reifwolff.dk/columnpics/Glass-tube%20system.gif>

<http://www.davidstrahan.com/blog/wp-content/uploads/2008/03/seamibiotic-algae-pond-300w.jpg>

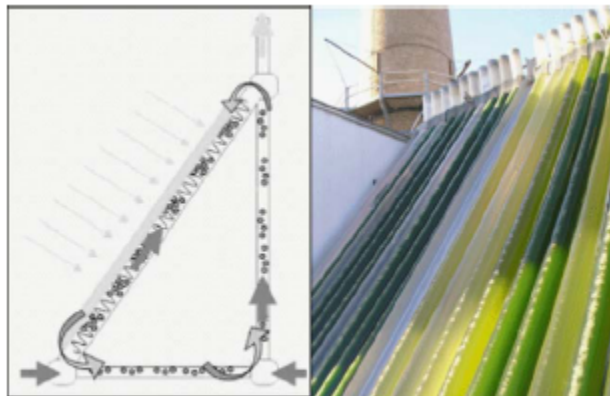


Fig. 5 GreenFuel's 3D Matrix Algae Growth Engineering Scale Unit, "triangle airlift reactor". At the left there is the drawing from patent US 20050260553, at the right the demonstration plant at the Red Hawk Power Plant, Arizona, USA [50]



# ***Big Companies, Government Agencies, and Investments are Targeting Algae***

- **DARPA, SAIC & General Atomics**
- **DOE & OriginOil**
- **Chevron & NREL**
- **ExxonMobil & Sapphire**

