Sustainability in Algae Biofuel Production

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Algae

Algae constitute a rich Biochemical Factory that remains largely untapped!

Global Annual Microalgae Production

Spirulina	3000 t DW	China, India, USA, Myanmar, Japan	Human/animal nutrition cosmetics, phycobili
Chlorella	2000 t DW	Taiwan, Germany, Japan	Human nutrition, aquaculture, cosmetics
Dunaliella salina	1200 t DW	Australia, Israel, USA, China	Human nutrition, cosmetics, b-carotene
Haematococcus pluvialis	300 t DW	USA, India, Israel	Aquaculture, astaxanthin
Crypthecodinium cohnii	240 t DHA oil	USA	DHA oil

Total = about 5000 t DW/yr, US$1.25 x 10^9/yr

1.0 Algae for Nutraceuticals

(Omega 3/6 -- DHA, EPA, AA)

Omega-3/6 Fatty Acids

DHA, EPA, AA

Reduce cardiovascular diseases and obesity

Play role in cellular and tissue metabolism, including the regulation of membrane fluidity, electron and oxygen transport, thermal adaptation (Cardozo 2007, Guaratini et al. 2007).

Products from Microalgae

Eicosapentaenoic Acid (EPA, 20:5n3)

	% TFA
Cod Liver Oil	**12.45**
Isochrysis galbana	**22.60**
Phaeodactylum tricornutum	**29.83**
Porphyridium cruentum	**23.90**

2.0 Algae for Animal Feeds

Algae as Feed:

Algae as Animal Feed

-- Improved immune response, improved fertility, better weight control, healthier skin and a lustrous coat (Pulz and Gross 2004)

-- Adding algae to the diet of cows resulted in a lower natural breakdown of unsaturated fatty acids and a higher concentration of these beneficial compounds in meat and milk

-- Improves the color of the skin, shanks and egg yolks of poultry

3.0 Algae for Fish Production

Algae:

Algae as Fish Feed

-- For hatchery and nursery of bivalves, shrimp, and some finfish cultures

-- For producing zooplankton, typically rotifers, which are fed to the freshly hatched carnivorous fish (Benemann and Oswald 1996)

-- 62% for mollusks, 21% for shrimps and 16% for fish

China's Zhejiang Mariculture Research Institute

4.0 Algae for Cosmetics

Algae:

Algae for Cosmetics

-- For anti-aging cream, regenerating care products, emollient, anti-irritant in peelers, sun protection and hair care products

-- Repair signs of early skin aging, exert skin-tightening effect, prevent stria formation and stimulate collagen synthesis in skin (Spolaore et al. 2006).

5.0 Algae for Biofuels

Algae: Biodiesel Yield (L/ha-yr)

Soybeans	446
Rapeseed	119
Mustard	1300
Jatropha	1892
Palm Oil	5950
Algae (Low)	45000
Algae (High)	137000

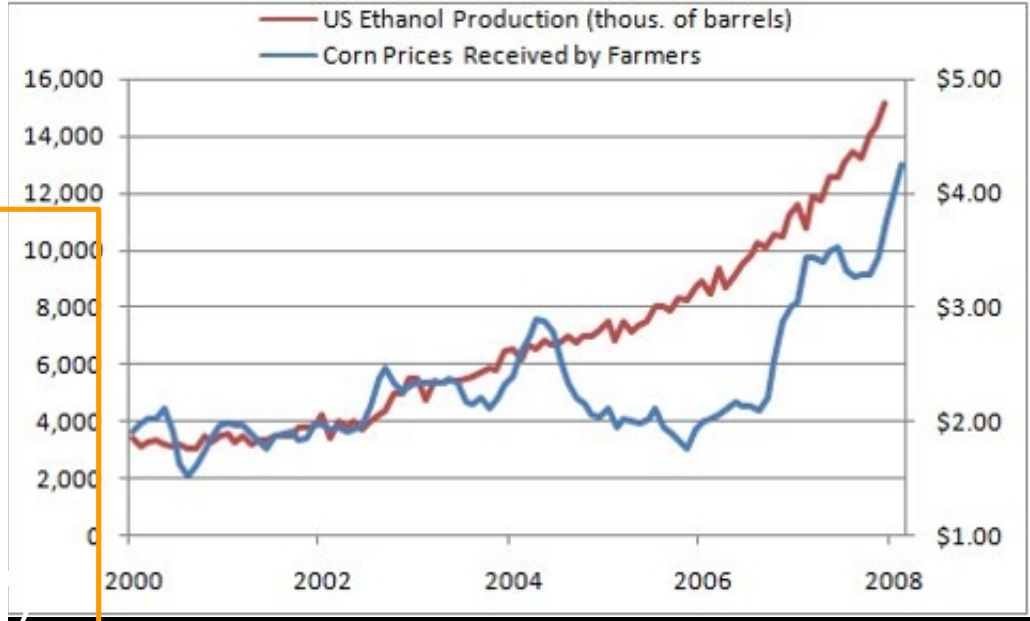
Food Vs. Fuel

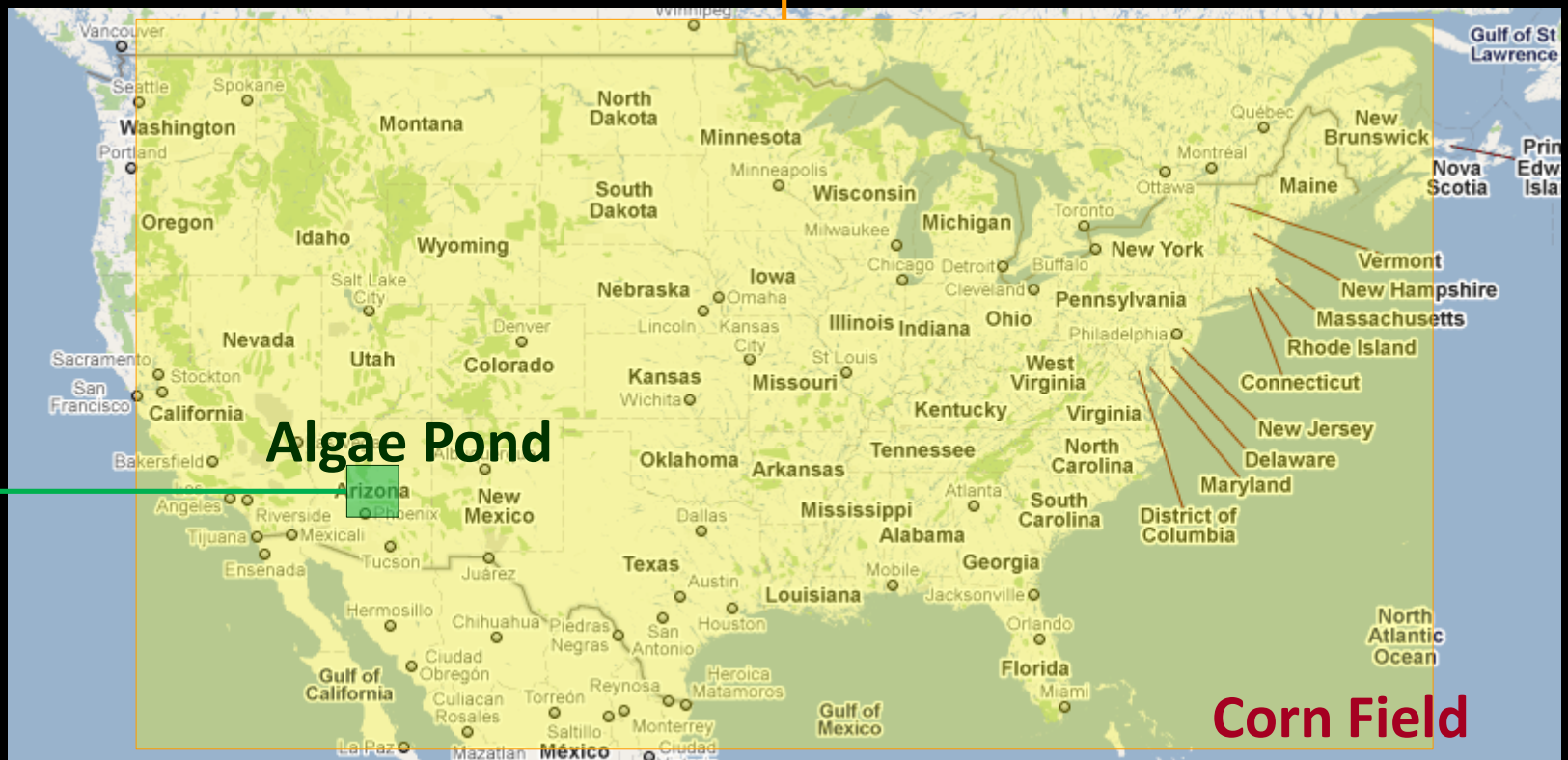
Food Wins!

Table 1
Comparison of some sources of biodiesel

Crop	Oil yield (L/ha)	Land area needed (M ha) [a]	Percent of existing US cropping area [a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1190	223	122
Jatropha	1892	140	77
Coconut	2689	99	54
Oil palm	5950	45	24
Microalgae [b]	136,900	2	1.1
Microalgae [c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.





Algae:

- Can accumulate hydrocarbons
- Can accumulate fatty acids
- Can accumulate starch
- Can synthesize hydrogen gas

Biofuel / Nutraceutical Production from Algae

Species/Strain Selection

↓

Mass Production of Algae

↓

Harvesting

↓

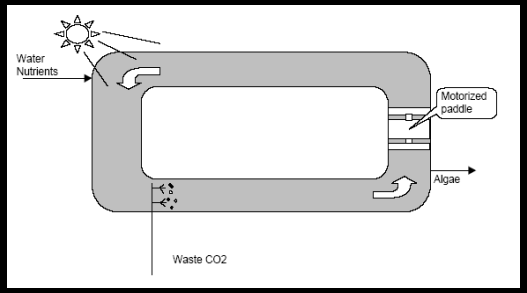
Dewatering

↓

Product Extraction/Processing

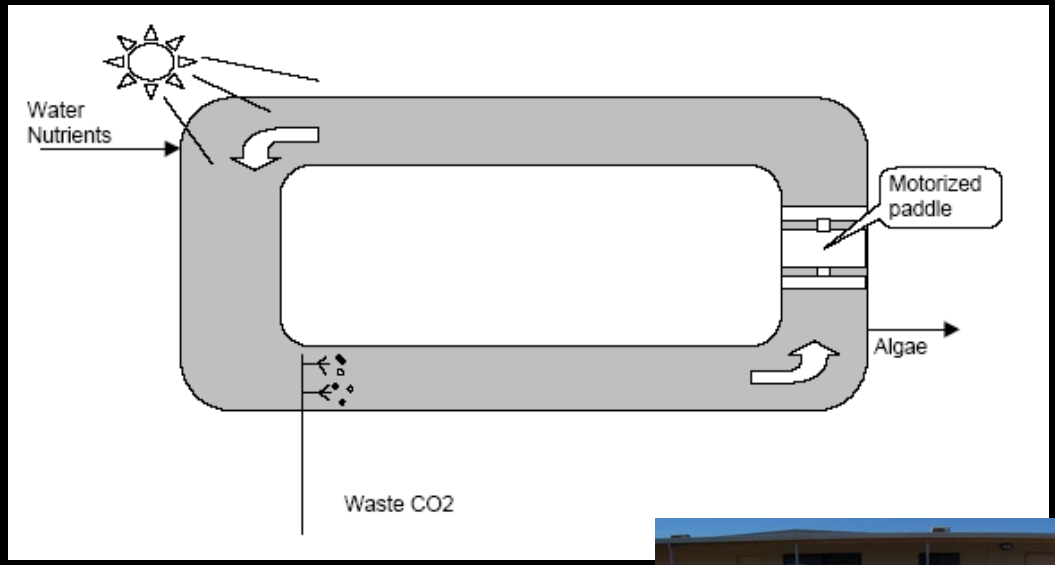
Two Ways to Mass Produce Algae:

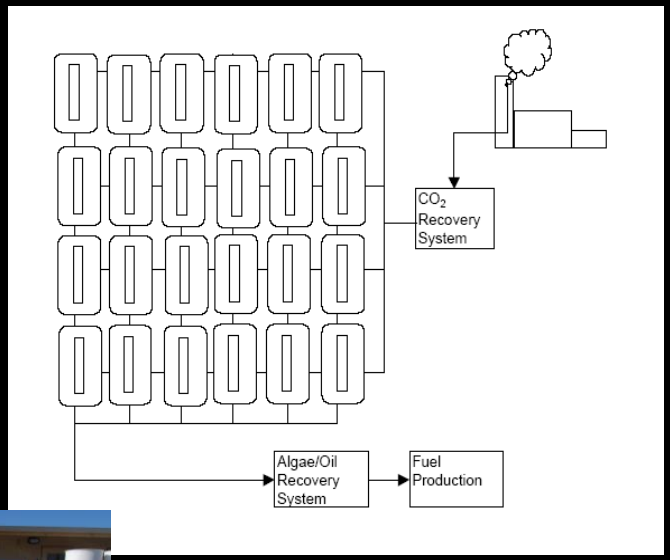
Open Ponds



Photobioreactors

Open Pond System





Open Pond System

Open Pond System

Open Pond System

Cyanotech, Hawaii

Photobioreactors

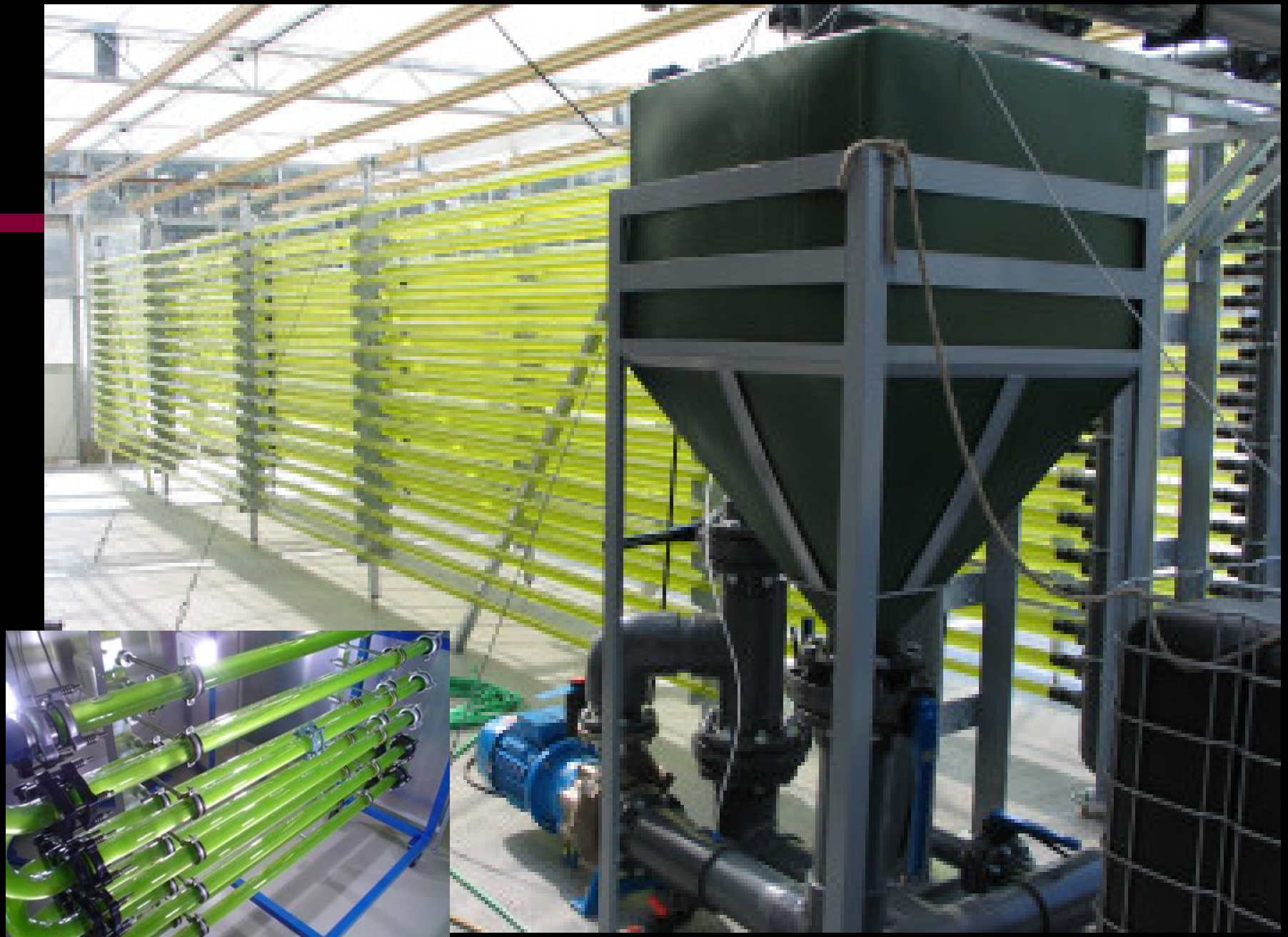
Controlled

Light
Nutrients
CO_2
Mixing
Culture Density
pH
Temperature
Flow Rate
etc.

Photobioreactor Designs

Photobioreactor Designs

Photobioreactor Designs



Photobioreactors

Photobioreactor Designs

Algae for Biofuels and Other Products

Require:

Techno-economic Feasibility

AND

Environmental Sustainability

Algae for Biofuels and Other Products

Environmental Sustainability:

- Water use
- Nutrients use
- Land use
- Energy use

Comparisons

	Open Ponds	Photobioreactors
Capital Cost	+	-
Energy	+	-
Land Area	-	+
Water Loss	-	+
Productivity	-	+
Risk of contamination	-	+

Because of expensive materials used (glass, PVC)

Environmental sustainability criteria must be part of system assessment

Innovative Strategy 1

Algenol Approach

Microalgae Production Pathway

Species/Strain Selection

↓

Mass Production

↓

~~Harvesting~~

↓

~~Dewatering~~

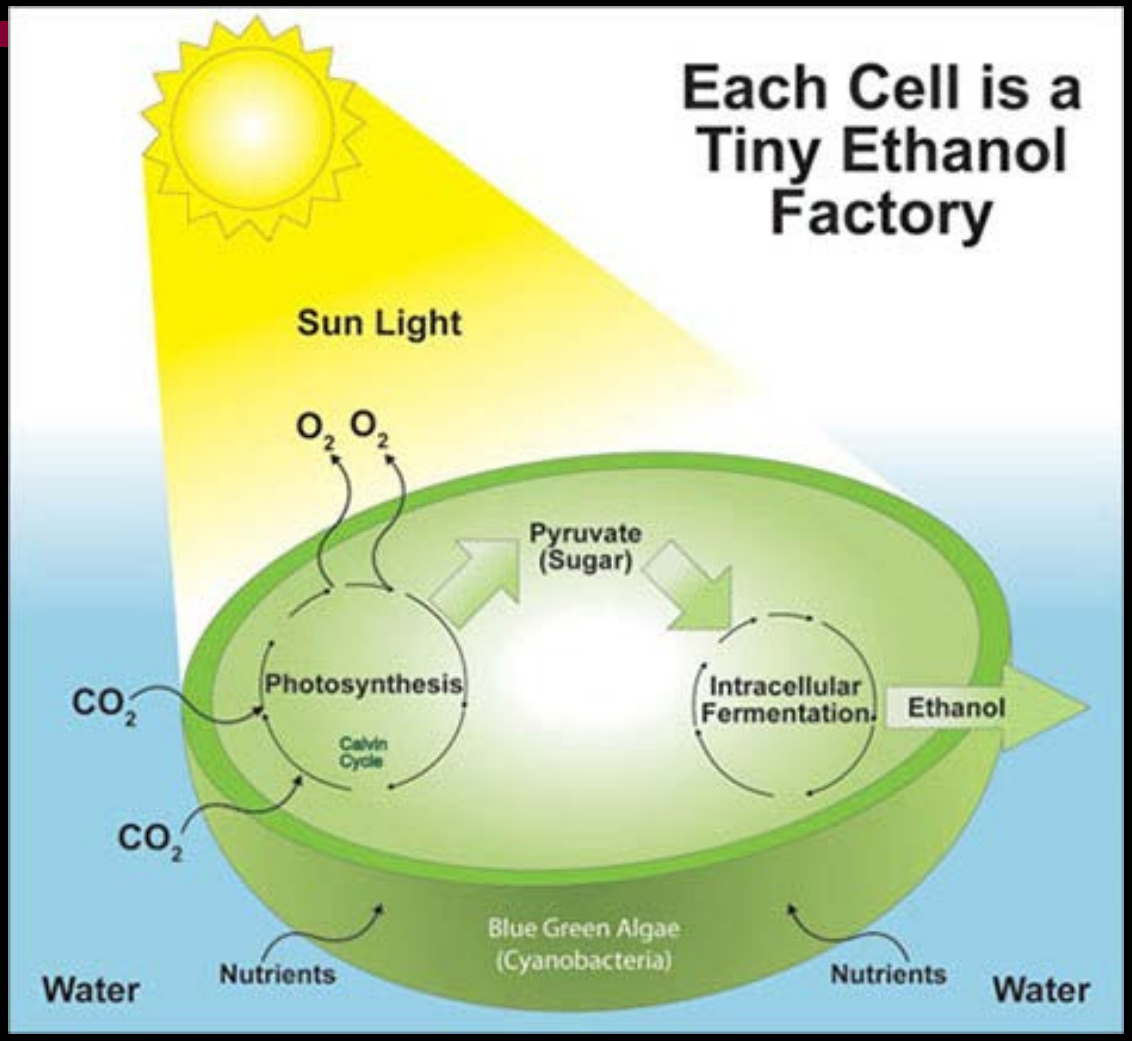
↓

~~Product Extraction~~

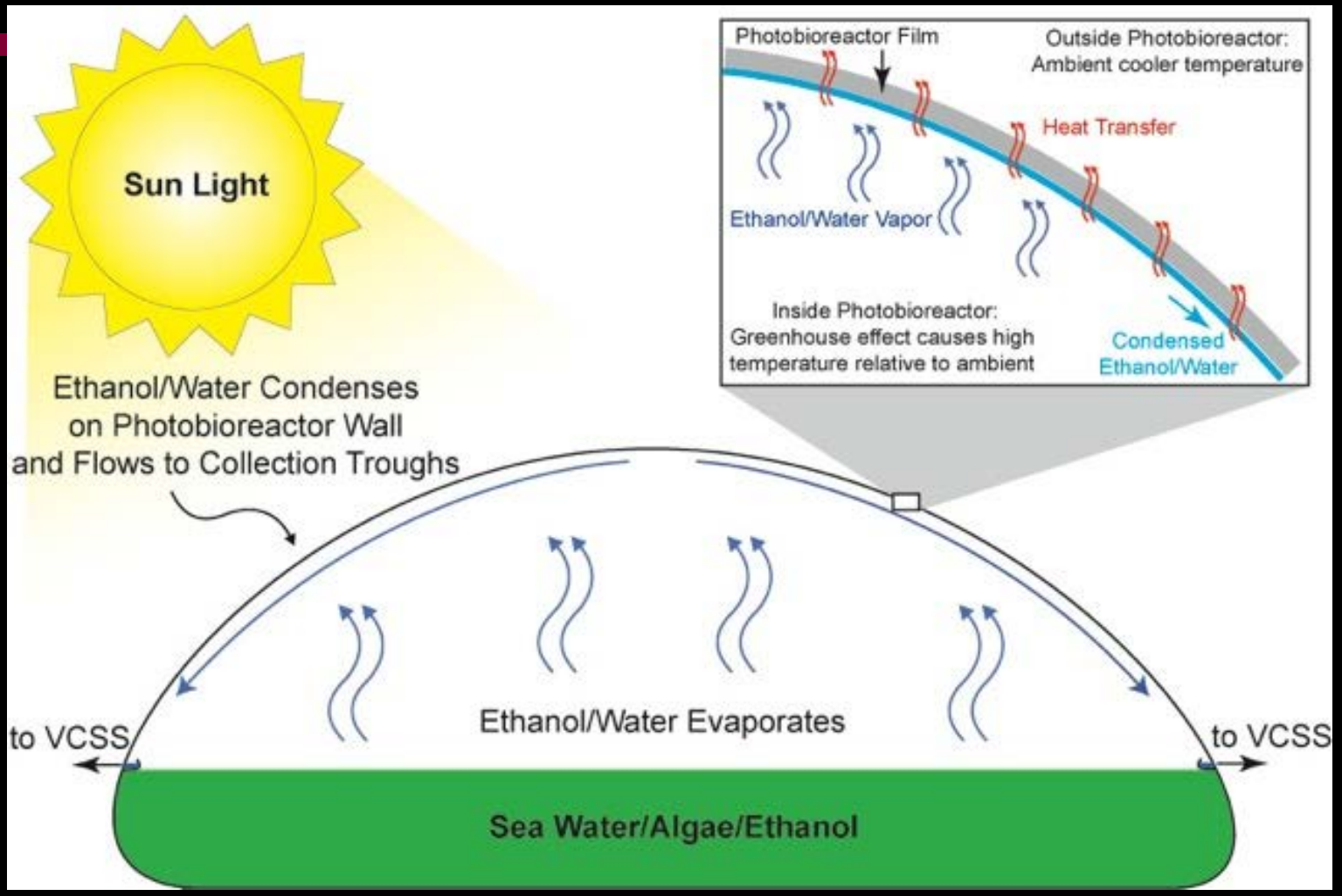
↓

Product Separation

Algenol, U.S.A.


Each Cell is a Tiny Ethanol Factory
Sun Light
O_2 O_2
Pyruvate (Sugar)
CO_2
Photosynthesis
Calvin Cycle
Intracellular Fermentation
Ethanol
CO_2
Blue Green Algae (Cyanobacteria)
Water
Nutrients
Nutrients
Water

Algenol, U.S.A.


Sun Light
Ethanol/Water Condenses on Photobioreactor Wall and Flows to Collection Troughs
Photobioreactor Film
Outside Photobioreactor: Ambient cooler temperature
Heat Transfer
Ethanol/Water Vapor
Inside Photobioreactor: Greenhouse effect causes high temperature relative to ambient
Condensed Ethanol/Water
to VCSS
Ethanol/Water Evaporates
to VCSS
Sea Water/Algae/Ethanol

Algenol, U.S.A.


CO2 from
Power Plant
Nutrients
Solar
Radiation
Gas
Treatment
Blue-green Algae
Oxygen
Separation
Process
Unproductive Land
Seawater
(Fresh Water)
Bioethanol

Algenol, U.S.A.

Algenol, U.S.A.

Microalgae Production Pathway

Species/Strain Selection

↓

Mass Production ← Water, Nutrients, Cyanobacteria

↓

~~Harvesting~~

↓

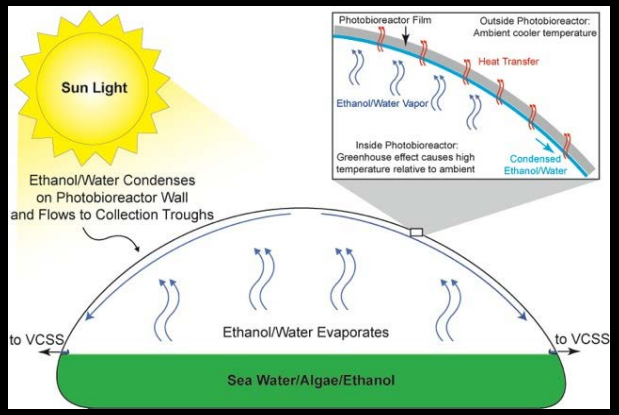
~~Dewatering~~

↓

~~Product Extraction~~

↓

Product Separation → Water

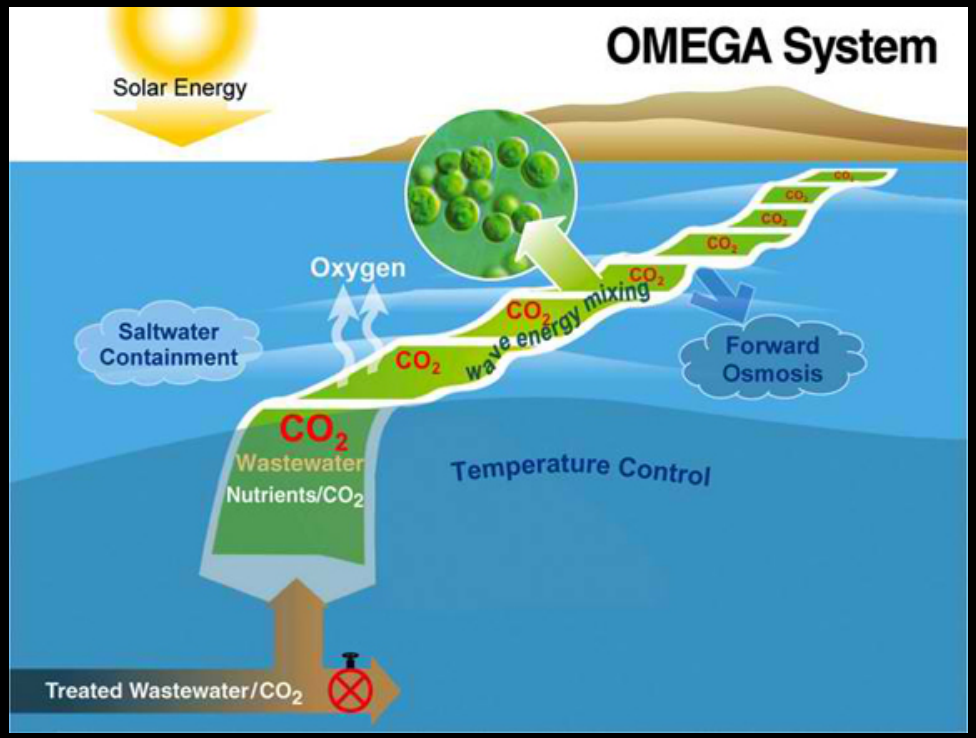


Innovative Strategy 2

Innovative Strategy 2:

Designing Novel, Low-Cost and Sustainable Photobioreactors

NASA's Offshore Membrane Enclosure for Growing Algae (OMEGA)



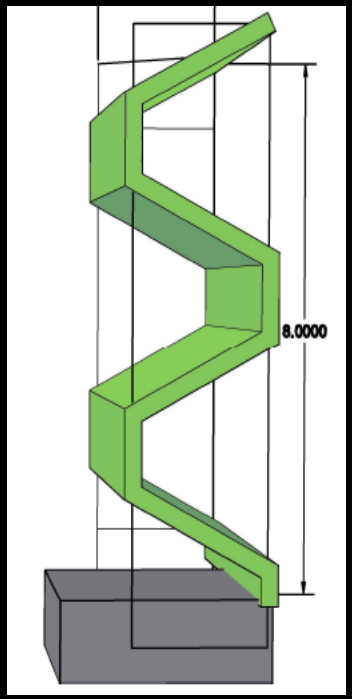
ACCORDION Photobioreactor

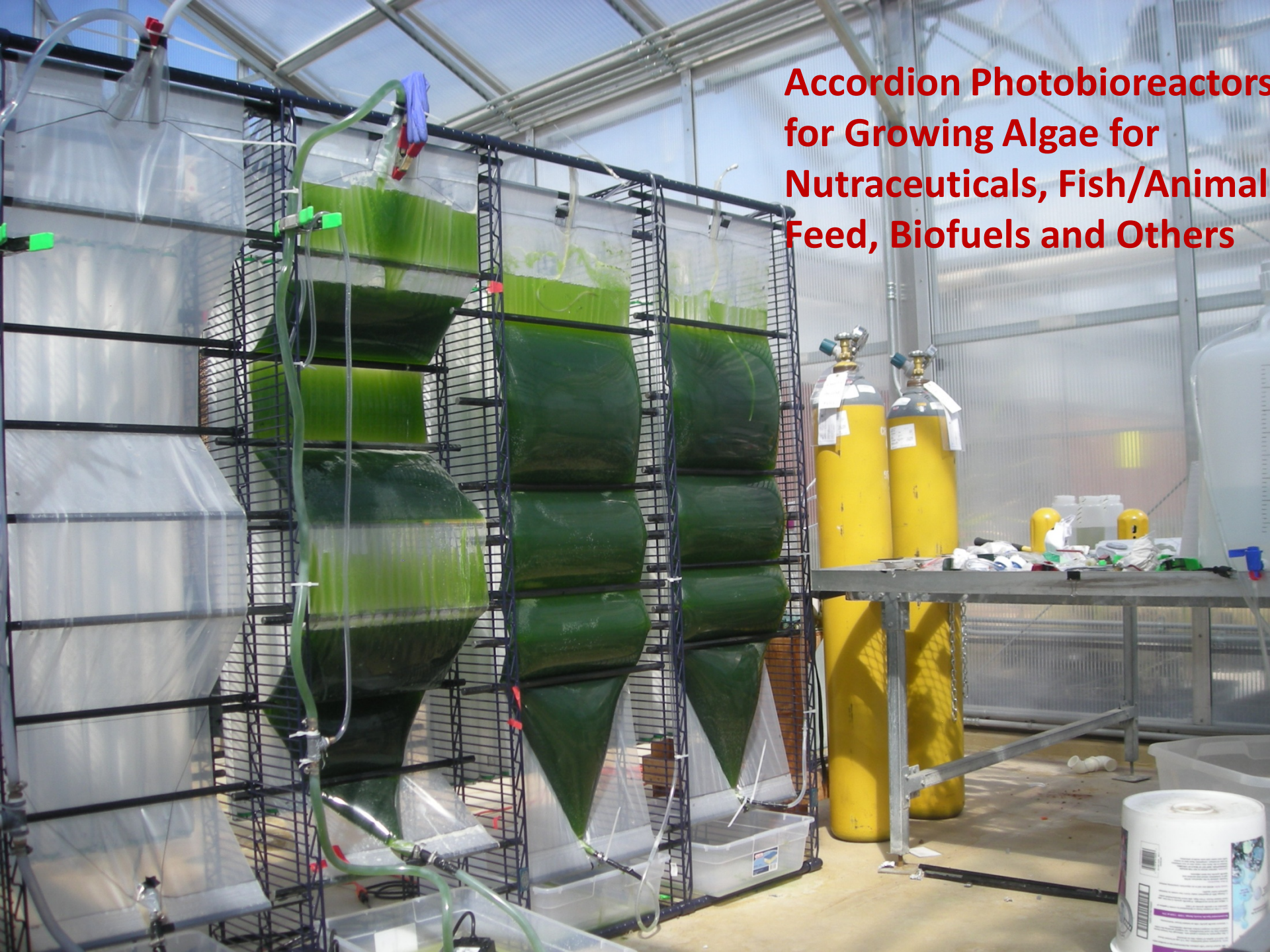
Low-Cost and High-Performance Photobioreactor

ACCORDION Photobioreactor

U.S. and International Patents Pending

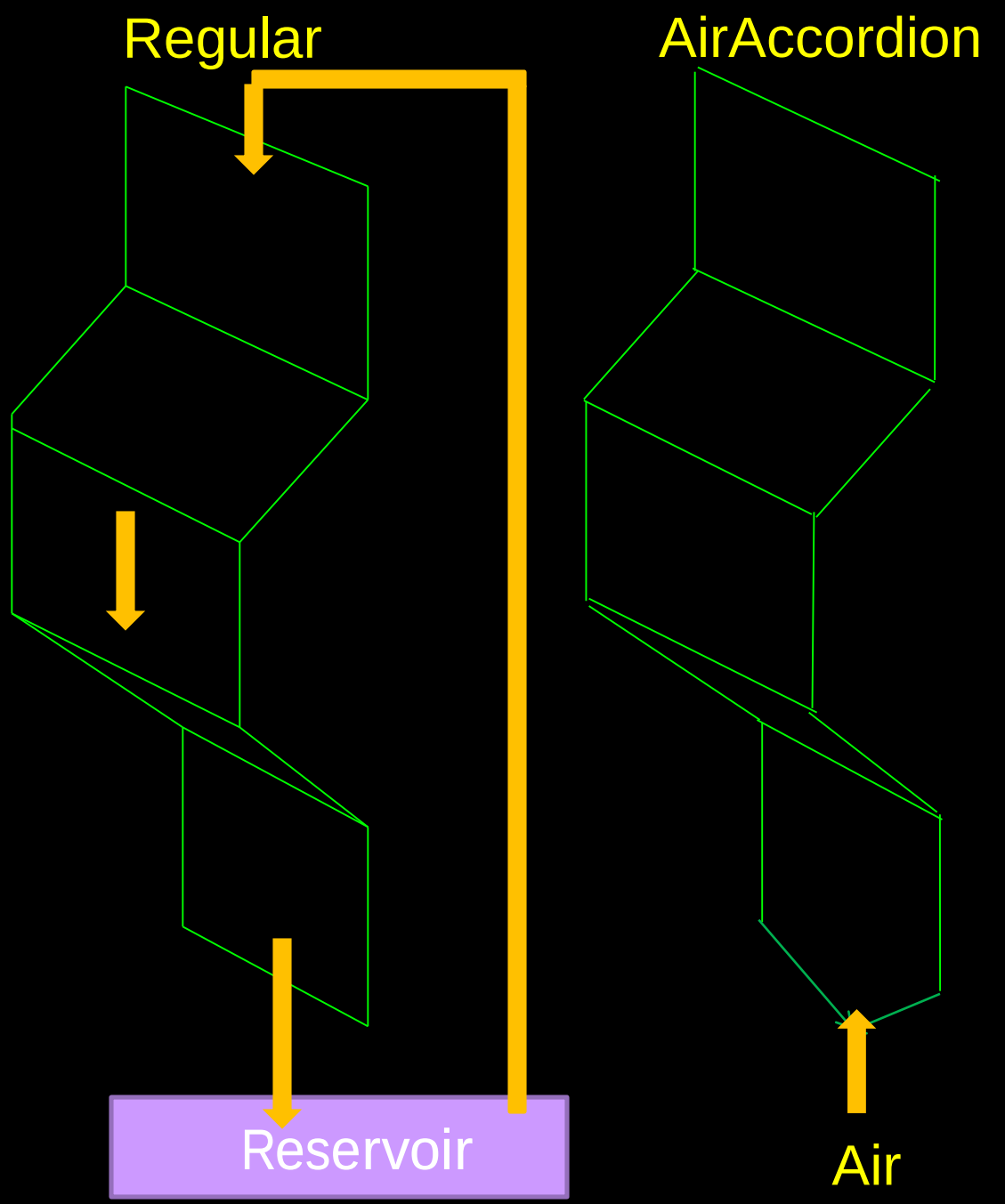
Licensed to Biopharmia, LLC



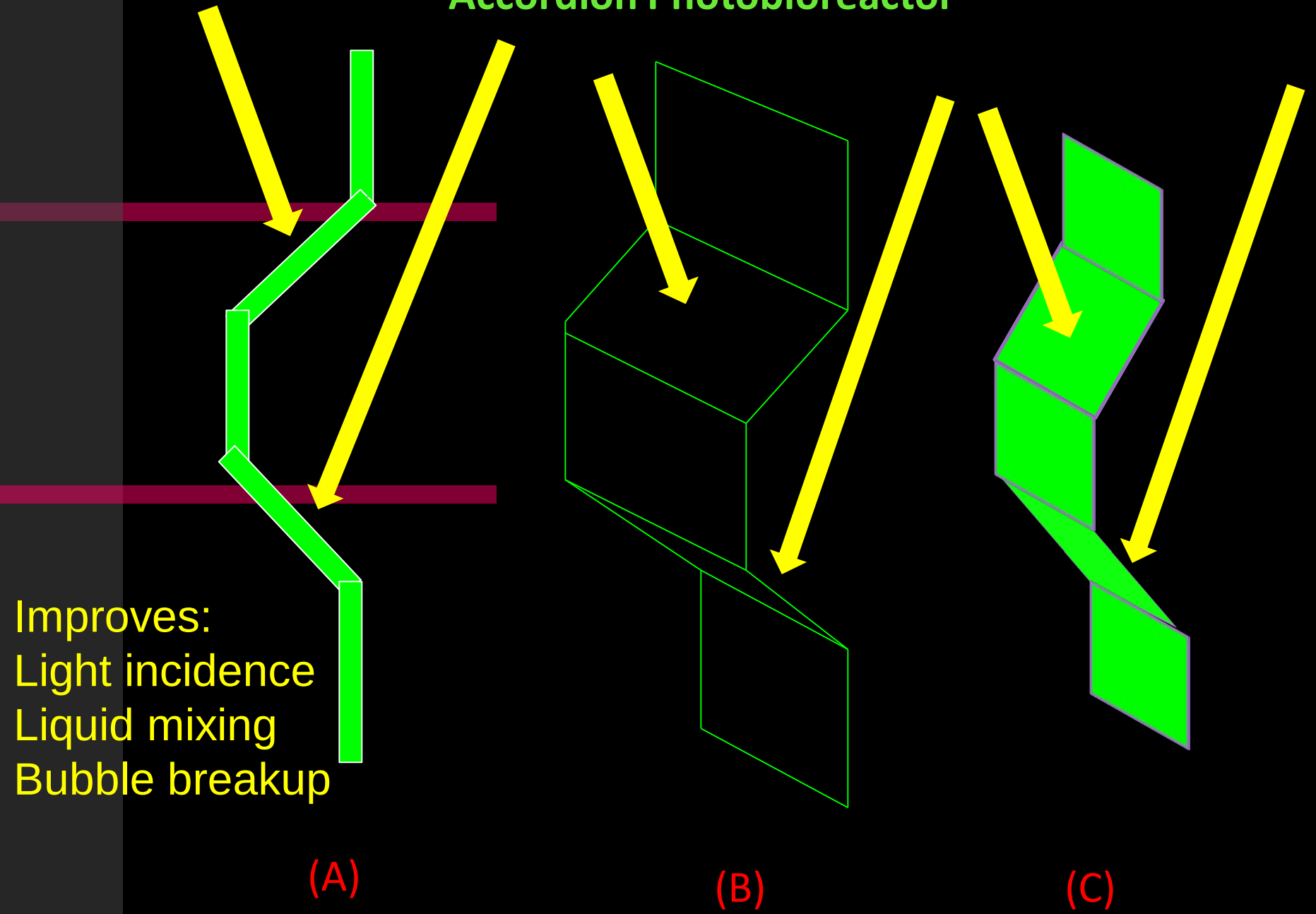

Accordion Photobioreactors
for Growing Algae for
Nutraceuticals, Fish/Animal
Feed, Biofuels and Others

ACCORDION Photobioreactor

Vertical series of angled flat plates



Accordion Photobioreactor

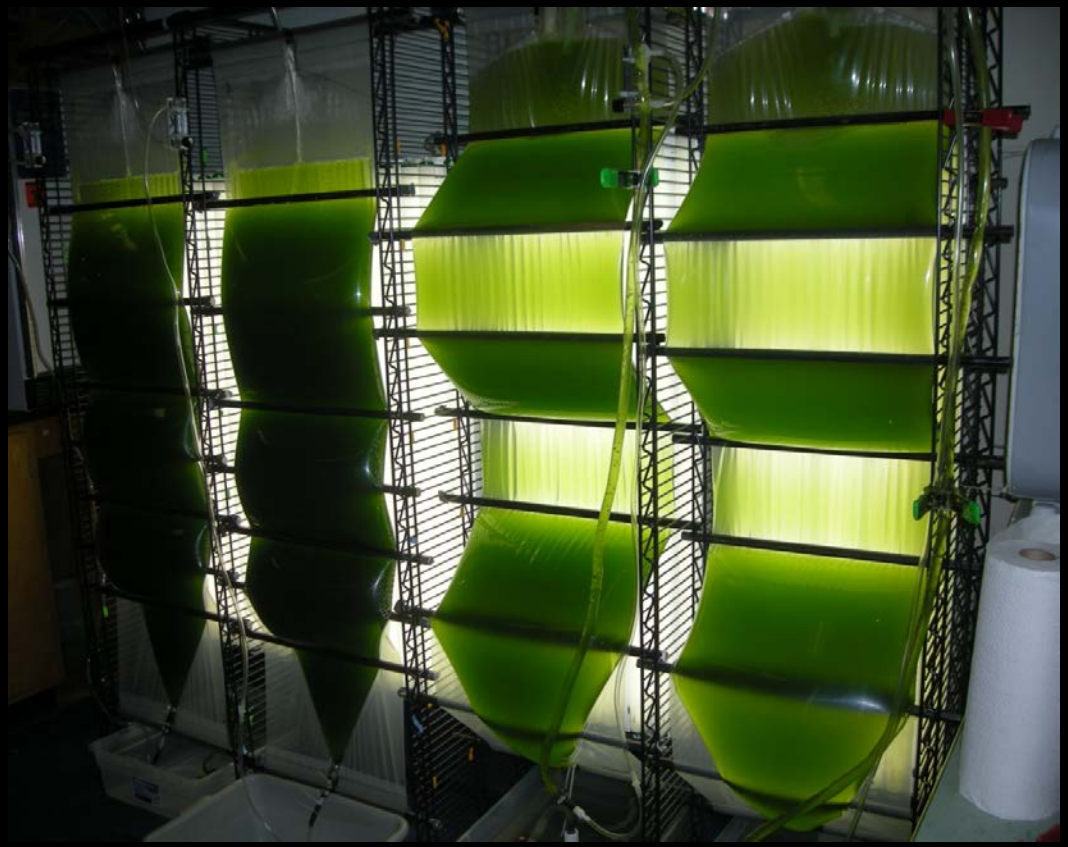


Improves:
Light incidence
Liquid mixing
Bubble breakup

(A) (B) (C)

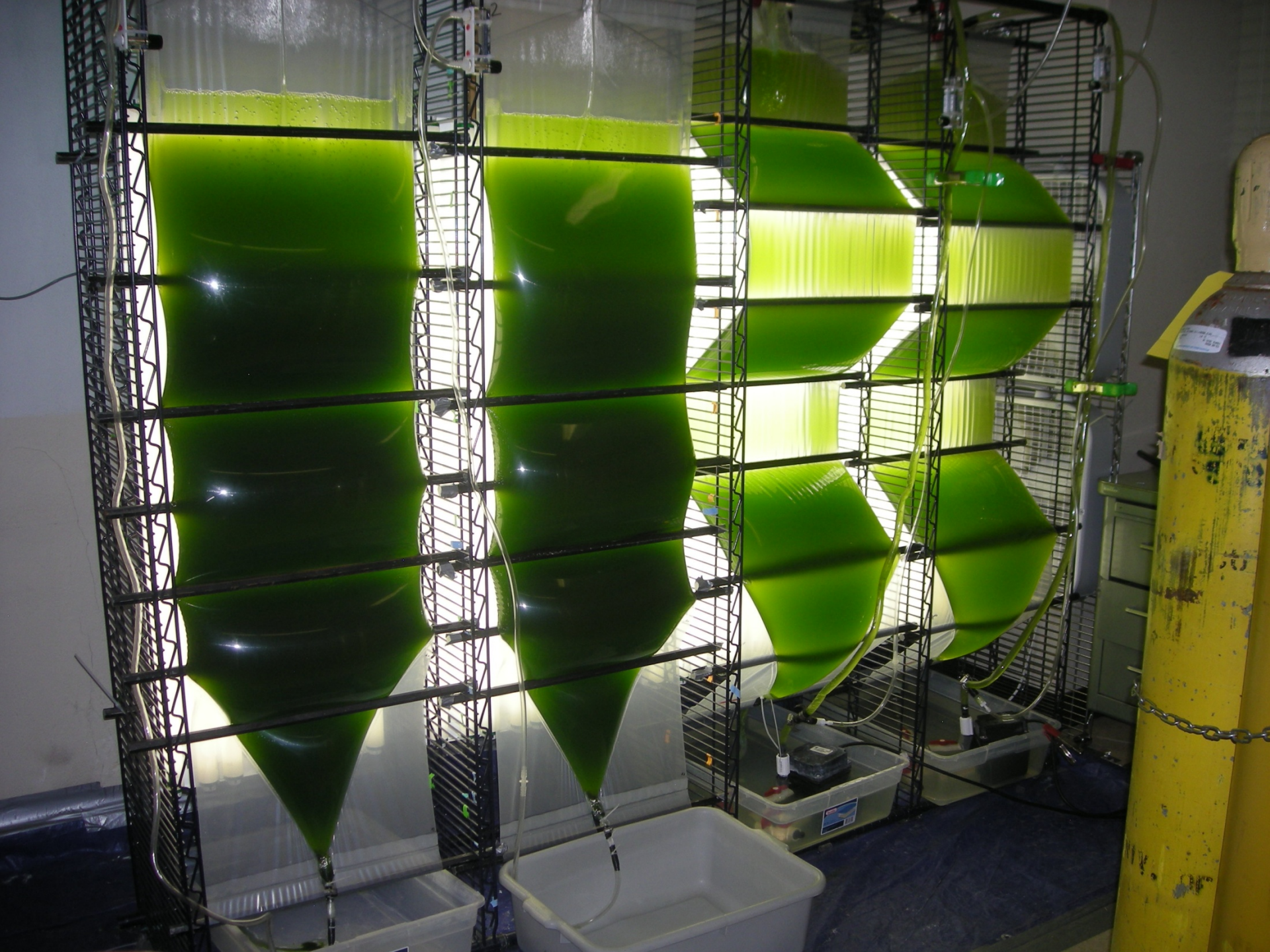
ACCORDION Photobioreactor

A Vertical series of angled flat plates

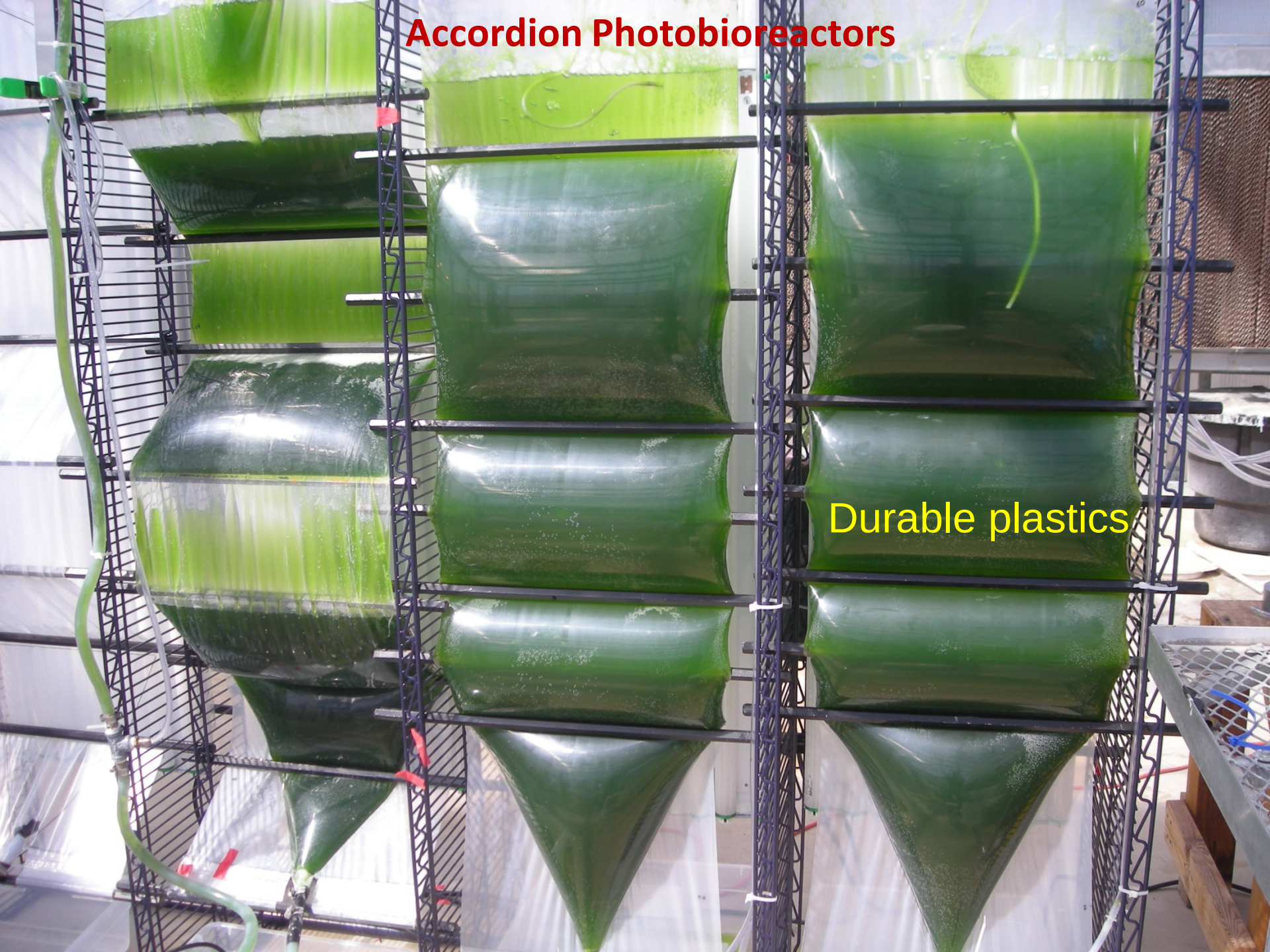


Advantages:

Low-cost
Simple design
Modular design
Simple maintenance
Lower power requirement
Adjustable light incidence
Adjustable flow
Ease of scale up
Ease of harvesting



Accordion Photobioreactors



Accordion Photobioreactors

Accordion Photobioreactors

Microalgae Production Pathway

Species/Strain Selection

↓

Mass Production

↓

Harvesting

↓

Dewatering

↓

Product Extraction

↓

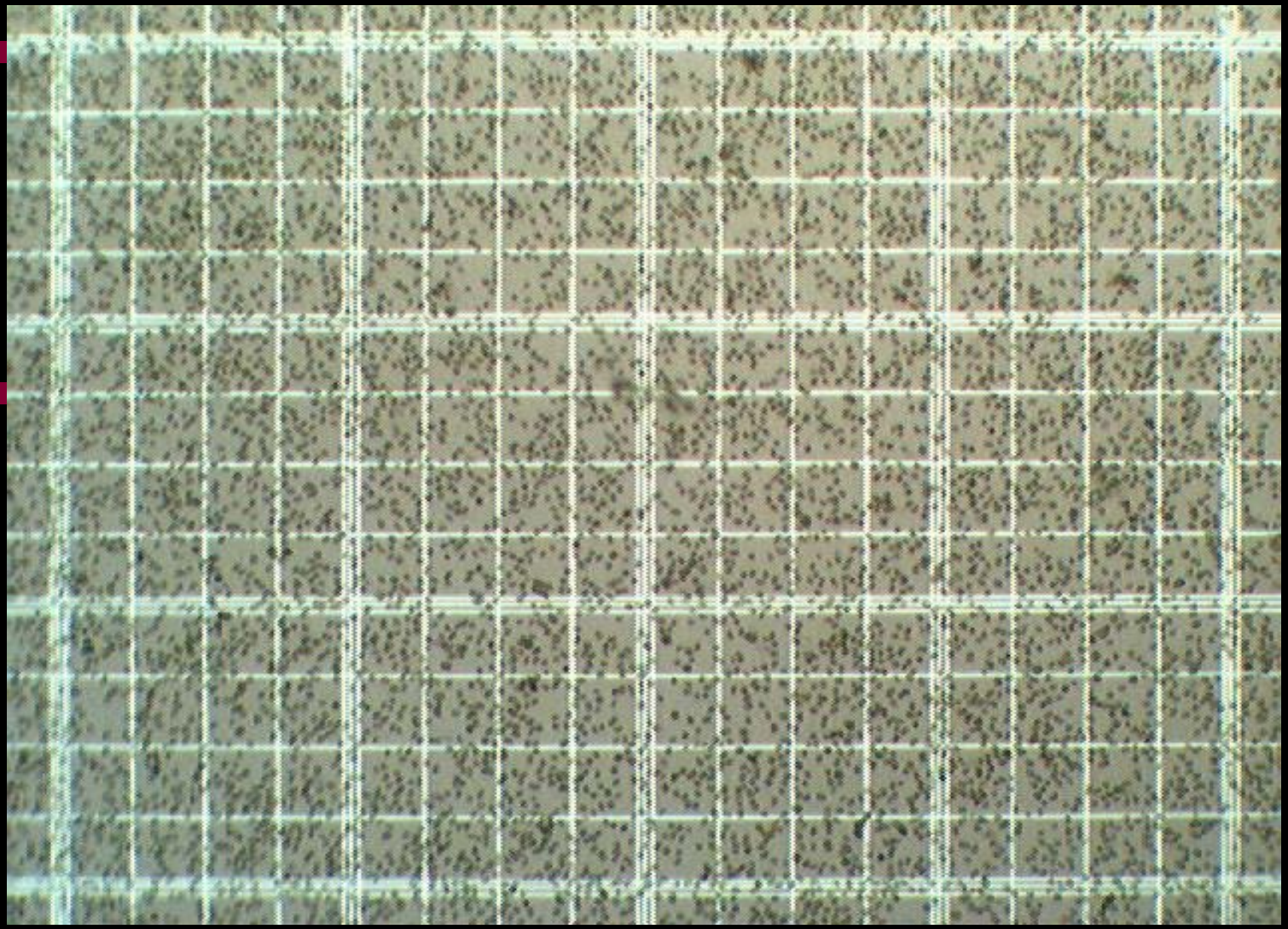
Conversion

Water & Nutrients Recycle

Minimal water loss

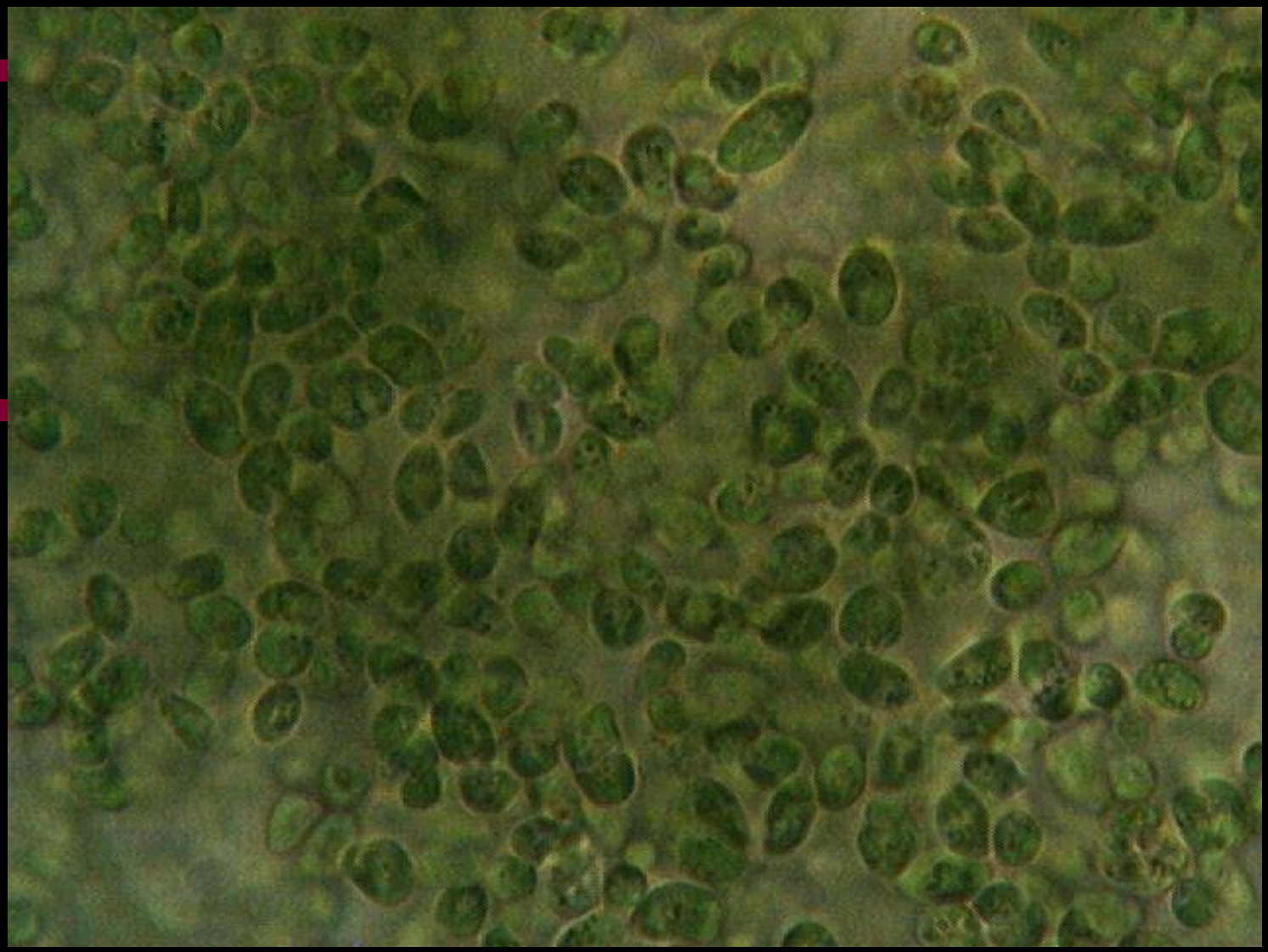
M. subterraneus in Accordion PBR in Greenhouse

Day 24



M. subterraneus in Accordion PBR in Greenhouse

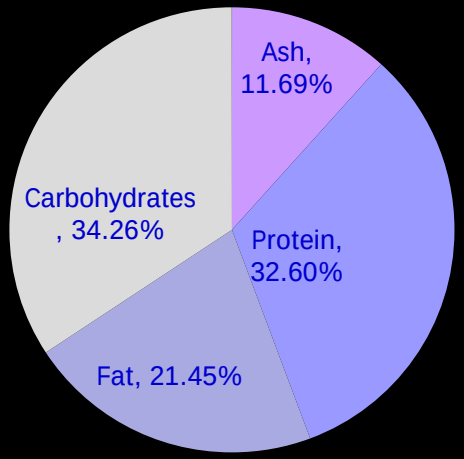
Day 24



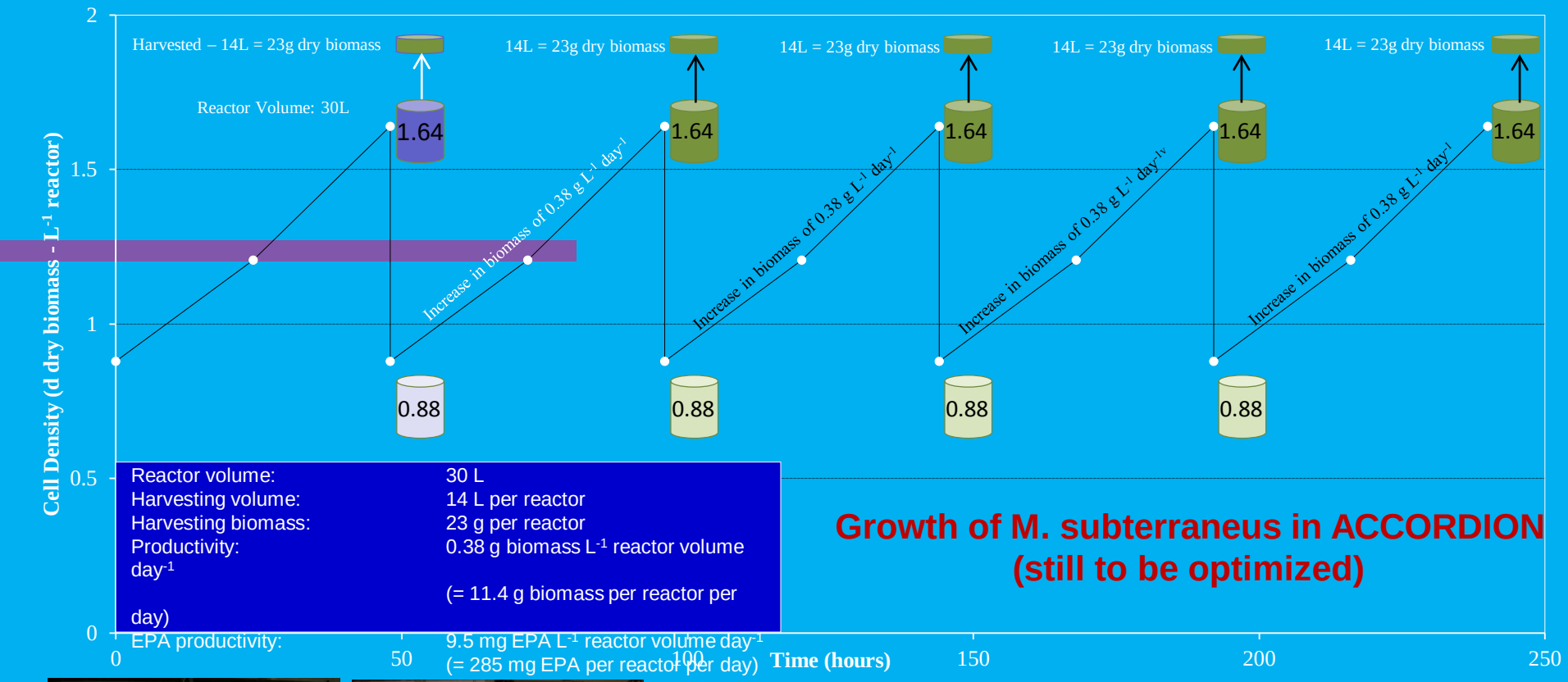
EPA contents and Growth of *M. subterraneus* in ACCORDION and control Laboratory Flask

	Flask (1 L)	Air Accordion (35 L)
EPA content (% biomass)	2.0 - 2.8%	2.2 - 2.86%
EPA content (% total Fatty Acids)	17 - 21%	20 - 22%
Total Fatty Acid (% biomass)	12 - 14%	11 - 13%
Max biomass productivity (g L^{-1} day^{-1})	0.198	0.433

Faster growth in Accordion

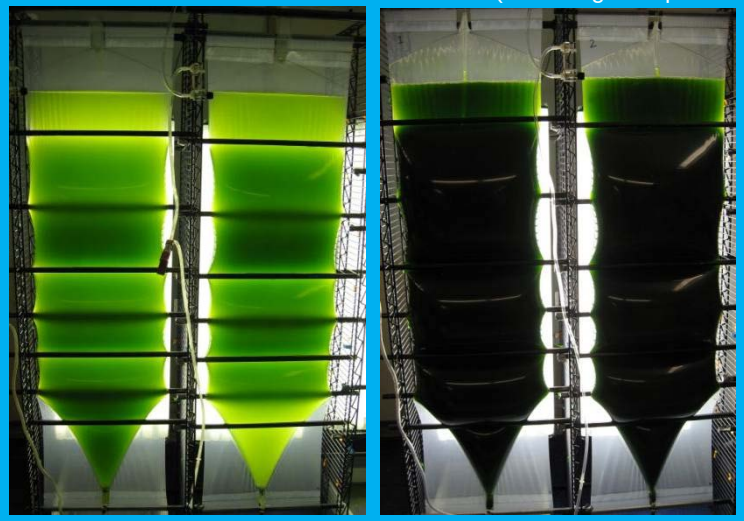


Authors	Photobioreactor	Volume (L)	Biomass Productivity / Area (g m^{-2} d^{-1})
Kuwahara et al. (2013)	Accordion	35	73.0
Lu et al. (2002)	Helical	75	64.5
Lu et al. (2002)	Bubble Column	57	35.8
Hu et al. (1996)	Flat Plate	25	36.2
Hu et al (1997)	Flat Plate	14	38.1
Vonshak et al. (2001)	Horizontal Tubular	140	9.5



Reactor volume:	30 L
Harvesting volume:	14 L per reactor
Harvesting biomass:	23 g per reactor
Productivity:	0.38 g biomass L^{-1} reactor volume day^{-1} (= 11.4 g biomass per reactor per day)
EPA productivity:	9.5 mg EPA L^{-1} reactor volume day^{-1} (= 285 mg EPA per reactor per day)

Growth of M. subterraneus in ACCORDION (still to be optimized)



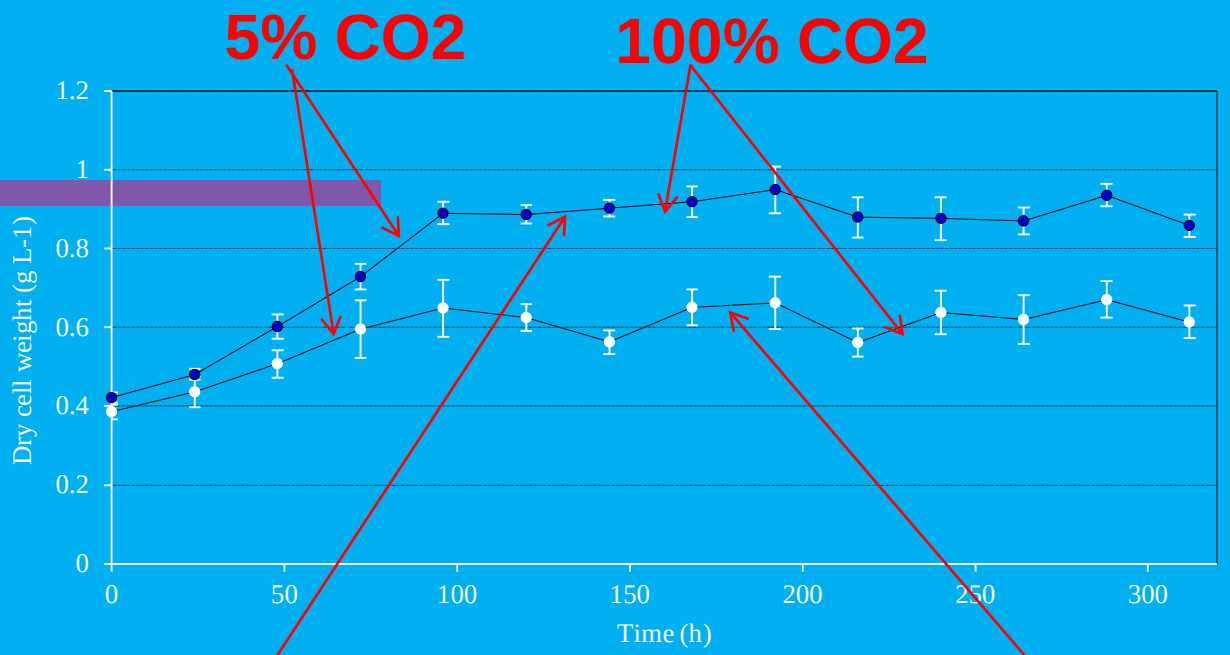
Time = 0 hours

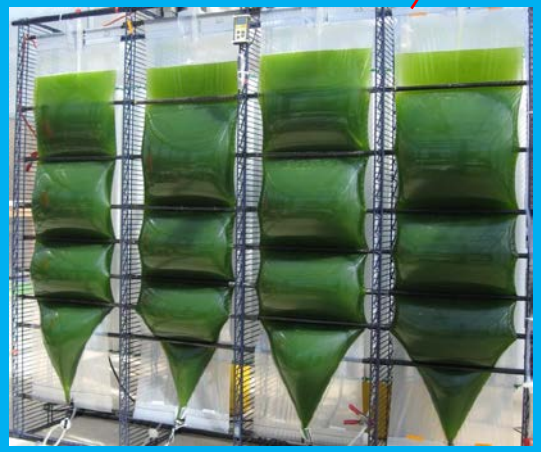
Time =192 hours

Objectives Achieved:

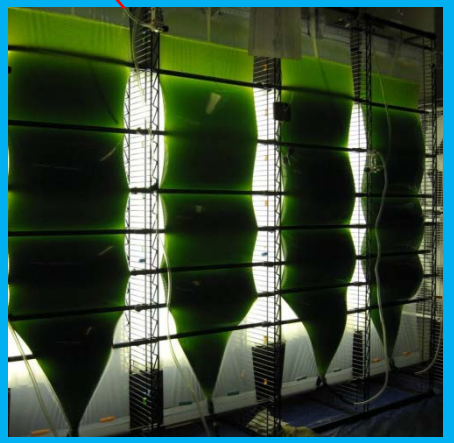
- ✓ High tolerance to CO_2, up to 25% CO_2 concentration and greater
- ✓ High productivity, up to 0.4 g biomass L^{-1} day^{-1} (= 8mg EPA L^{-1} day^{-1})
- ✓ Semi-continuous production for 3 weeks with negligible level of contamination
- ✓ Determined:
  - ✓ Positive dependence on CO_2 level (in the range of 5 – 25%CO_2).
  - ✓ Low dependence on light and nutrient level (in the range of 100 – 350 µmol m^{-2} s^{-1} in PAR).
  - ✓ Low shear stress (with pump flow rate less than 5 L min^{-1}).
  - ✓ Positive dependence on starting cell concentration (recommended initial cell concentration of 0.1-0.2 g L^{-1}).

Monodus subterraneous in ACCORDION: Carbon Dioxide Tolerance Study





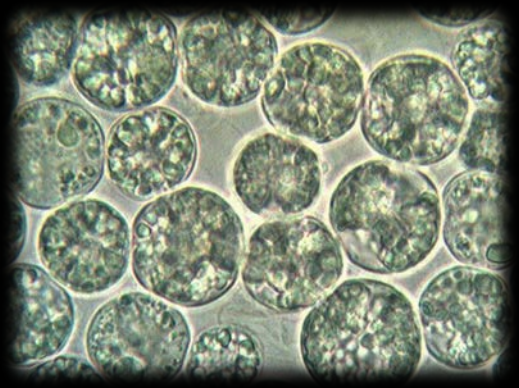
Greenhouse



Laboratory

Heterotrophic Production of *C. cohnii* in ACCORDION

DHA Content (% biomass)	1.3-2.2%
DHA Content (% total Fatty Acids)	21.5-24.6%
Total Fatty Acid (% biomass)	6.0-9.0%
Max biomass productivity (g L^{-1} day^{-1})	7.70



Microalgae Production Pathway 2

Species/Strain Selection

↓

Mass Production

↓

Harvesting

↓

Dewatering

↓

Product Extraction

↓

Conversion

Water
Nutrients

Minimal water losses

Innovative Strategy 3

Innovative Strategy 3: Cyanotech, U.S.A.

Hybrid PBR and Open-Raceway Production

Innovative Strategy 3: Cyanotech, U.S.A.

Hybrid PBR and Open-Raceway Production

Last 2 weeks of production only

PBRs

Open Raceways

Microalgae Production Pathway 3

Species/Strain Selection

↓

Mass Production

↓

Harvesting

↓

Dewatering

↓

Product Extraction

↓

Conversion

Water
Nutrients

Reduced Water
Losses

Algae for Biofuels and Other Products

Require:

Techno-economic Feasibility

AND

Environmental Sustainability

SAUDI ARABIA

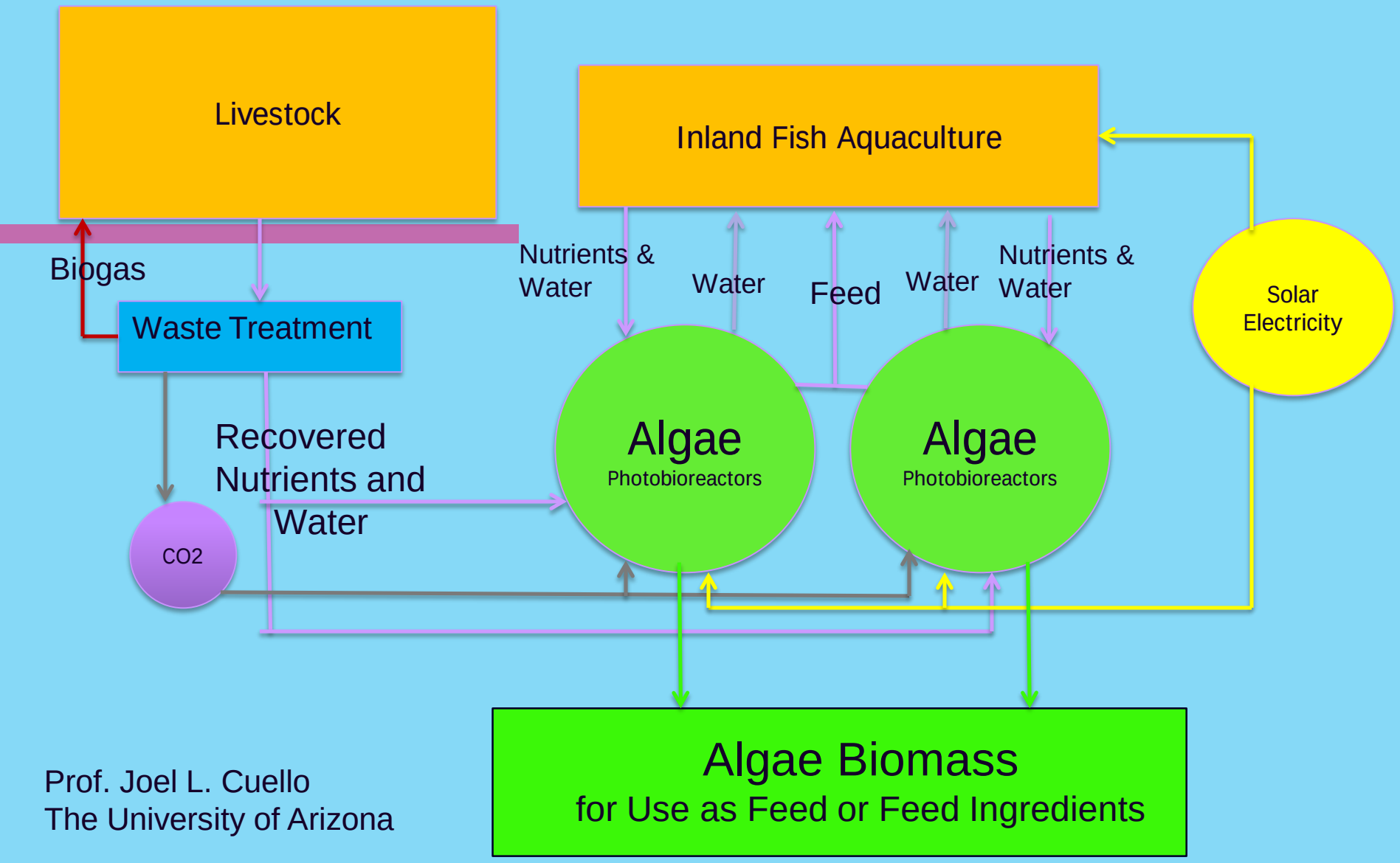

Riyadh, Saudi Arabia

King Abdulaziz City for
Science and Technology (KACST)


King Abdulaziz City for
Science and Technology (KACST)

Algae as Feed:

QATAR



Prof. Joel L. Cuello
The University of Arizona

Qatar Integrated Demonstration Farm

Chile

Universidad de Magallanes

Harnessing algae from Patagonia and Antarctica for biofuels and other high-value products

Acknowledgments


Wildcats
A&F

Roald A. Flo, Ph.D.
Managing Director PhD

Biopharmia, LLC
Oslo, Norway