UNIVERSITY OF Southampton

Micro-algal Biorefineries

Towards Establishing Value Chains for Bioenergy in Namibia

The Ministry of Fisheries & Marine Resource Institute,
Swakopmund, Namibia,
29th April and 30th April 2013

ACP S&T PROGRAMME

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Bioenergy and Organic Resources Group
Water and the Environment
Engineering and the Environment

National Renewable Energy Laboratory

NREL

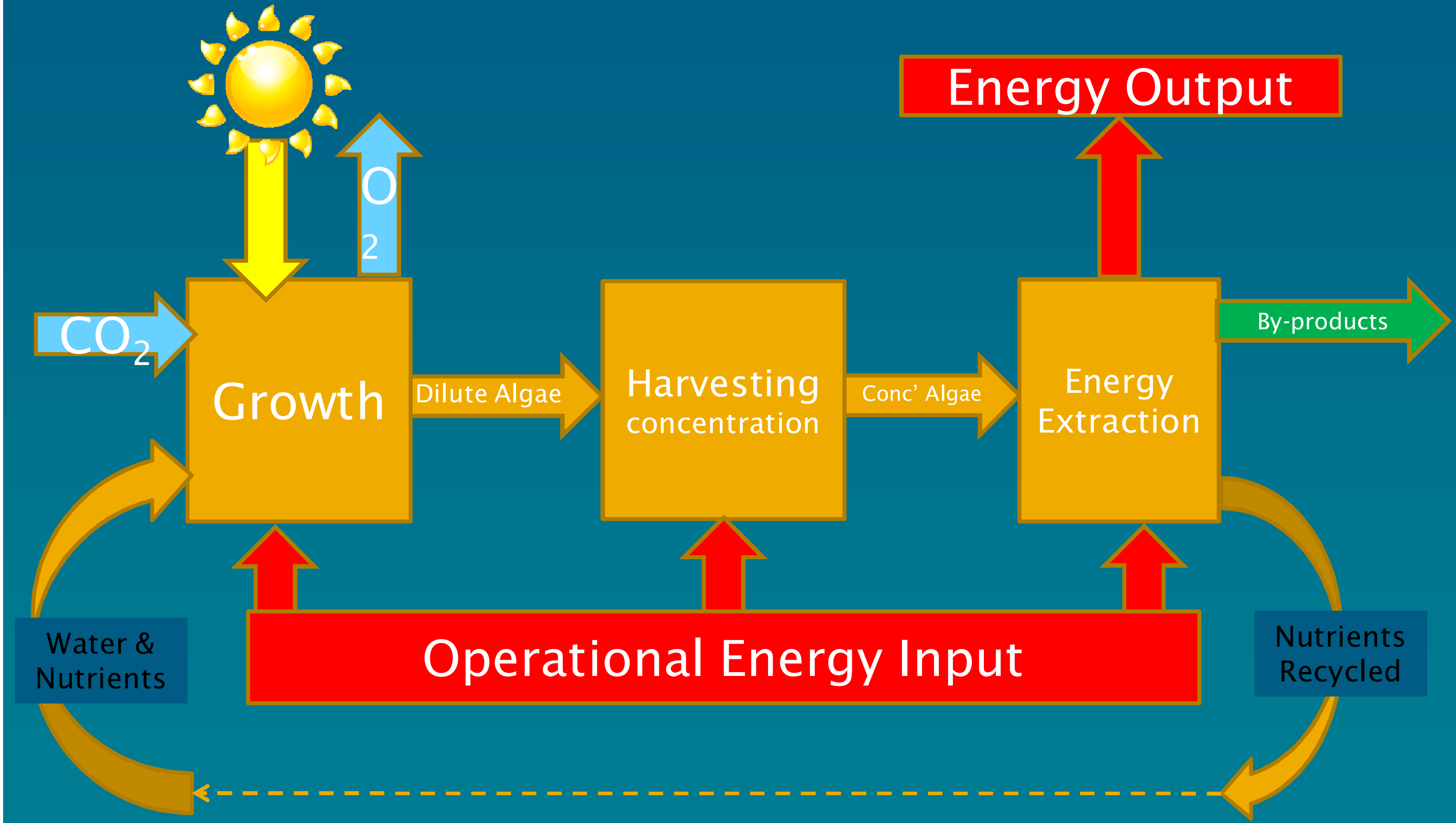
- From 1978 to 1996, the U.S. Department of Energy’s Office of Fuels Development funded a program to develop renewable transportation fuels from algae.

- The total cost of the Program was $25.05 million

- The overall conclusion of these studies was that in principle and practice large-scale microalgae production is not limited by design, engineering, or net energy considerations and could be economically competitive with other renewable energy sources

NREL, 1998. A Look Back at the U.S. Department of Energy’s Aquatic Species Program—Biodiesel from Algae.
http://www.nrel.gov/docs/legosti/fy98/24190.pdf

Algal Biofuel Process



Energy Output

O_2

CO_2

Growth

Dilute Algae

Harvesting
concentration

Conc' Algae

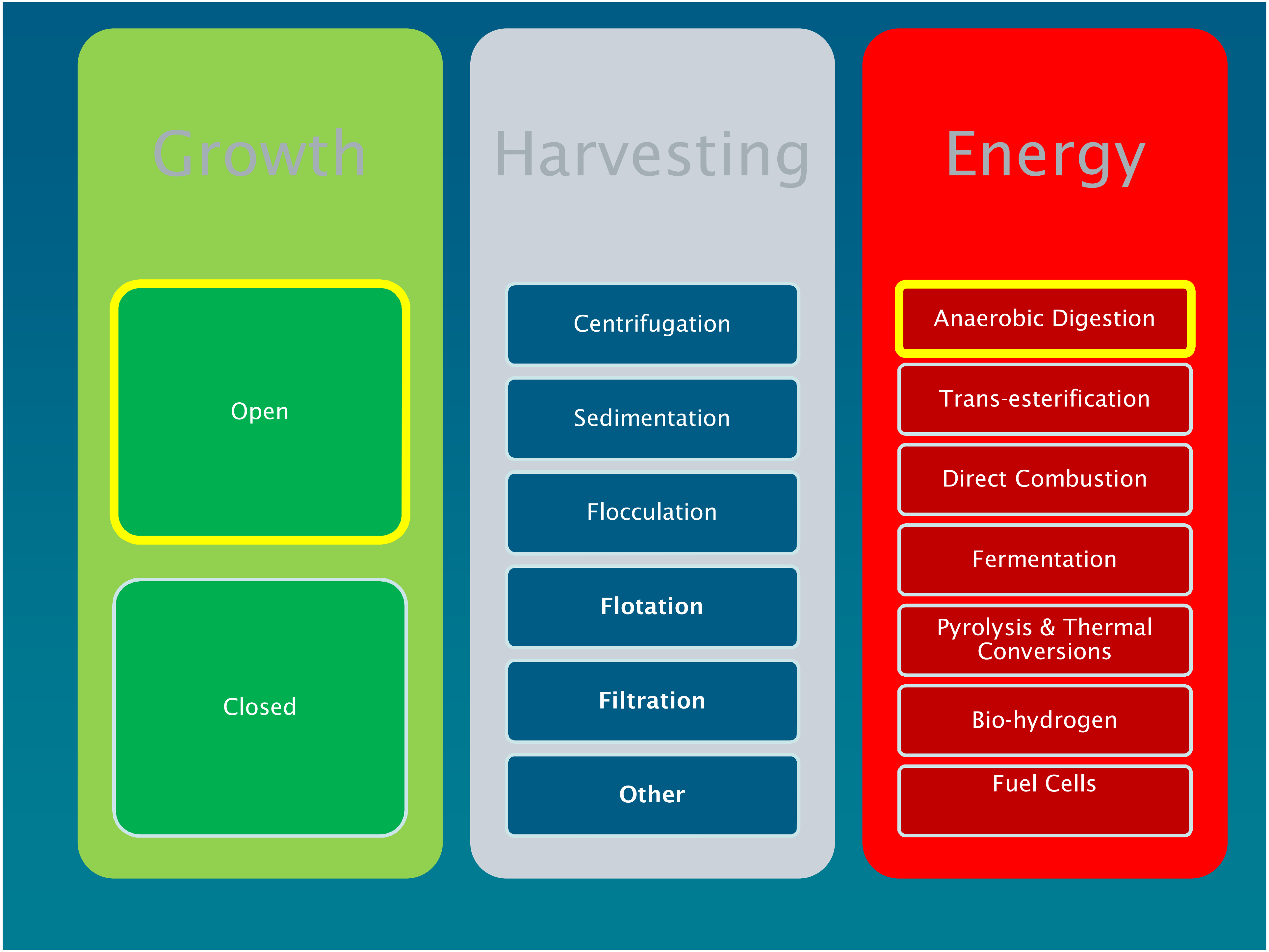
Energy
Extraction

By-products

Water &
Nutrients

Operational Energy Input

Nutrients
Recycled



Growth

- Open
- Closed

Harvesting

- Centrifugation
- Sedimentation
- Flocculation
- **Flotation**
- **Filtration**
- **Other**

Energy

- Anaerobic Digestion
- Trans-esterification
- Direct Combustion
- Fermentation
- Pyrolysis & Thermal Conversions
- Bio-hydrogen
- Fuel Cells

Micro-algal growth systems

Cajamar Experimental Station in Southern Spain

Open Experimental Raceway

Tubular Photo-bioreactor

Comparison of closed and open micro-algal growth systems

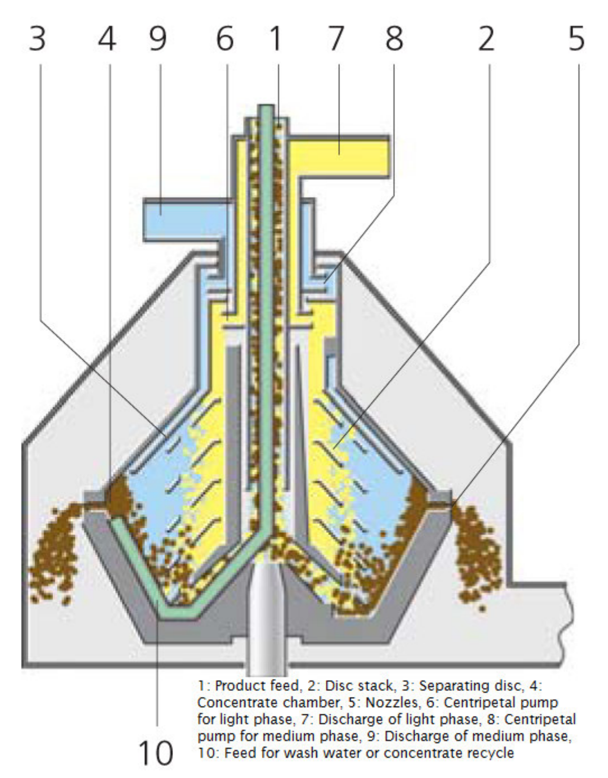
(adapted from Mata et al. (2010))

Culture systems for micro-algae	Closed systems (PBRs)	Open systems (Raceway Ponds)
Contamination control	Easy	Difficult
Contamination risk	Reduced	High
Process control	Easy	Difficult
Species control	Easy	Difficult
Mixing	Uniform	Very poor
Area/volume ratio	High (20–200 m^{-1})	Low (3–10 m^{-1})
Algal cell density	High	Low
Investment	High	Low
Operation costs	High	Low
Capital/operating costs ponds	Ponds 3–10 times lower cost	PBRs > Ponds
Light utilisation efficiency	High	Poor
Temperature control	More uniform	Difficult
Productivity	3–5x more productive	Low
Hydrodynamic stress on algae	Low–high	Very low
Evaporation of growth medium	Low	High
Gas transfer control	High	Low
O2 inhibition	Greater problem in PBRs	PBRs > Ponds
Biomass concentration	3–5 times in PBRs	PBRs > Ponds

MATA, T. M., MARTINS, A. A. & CAETANO, N. S. 2010. Microalgae for Biodiesel Production and Other Applications: A Review. Renewable & Sustainable Energy Reviews, 14,(1), 217-232.

Harvesting Micro-algae

A critical issue in the development of a commercially viable process for production of micro-algal biofuel



Disc Stack Centrifuge for Liquid/Liquid/Solid Separation (Courtesy GEA Westfalia

	Advantages	Disadvantages	Dry solids Output Concentration
Centrifugation	Can handle most algal types with rapid efficient cell harvesting.	High capital and operational costs.	10-22 %
Filtration	Wide variety of filter and membrane types available.	Highly dependent on algal species, best suited to large algal cells. Clogging and fouling an issue.	2-27 %
Ultrafiltration	Can handle delicate cells.	High capital and operational costs	1.5-4 %
Sedimentation	Low cost. Potential for use as a first stage to reduce energy input and cost of subsequent stages.	Algal species specific, best suited to dense non-motile cells. Separation can be slow. Low final concentration	0.5-3 %
Chemical flocculation	Wide range of flocculants available, price varies, although can be low cost.	Removal of flocculants and chemical contamination	3-8 %
Flotation	Can be more rapid than sedimentation. Possibility to combine with gaseous transfer.	Algal species specific. High capital and operational cost.	>7%

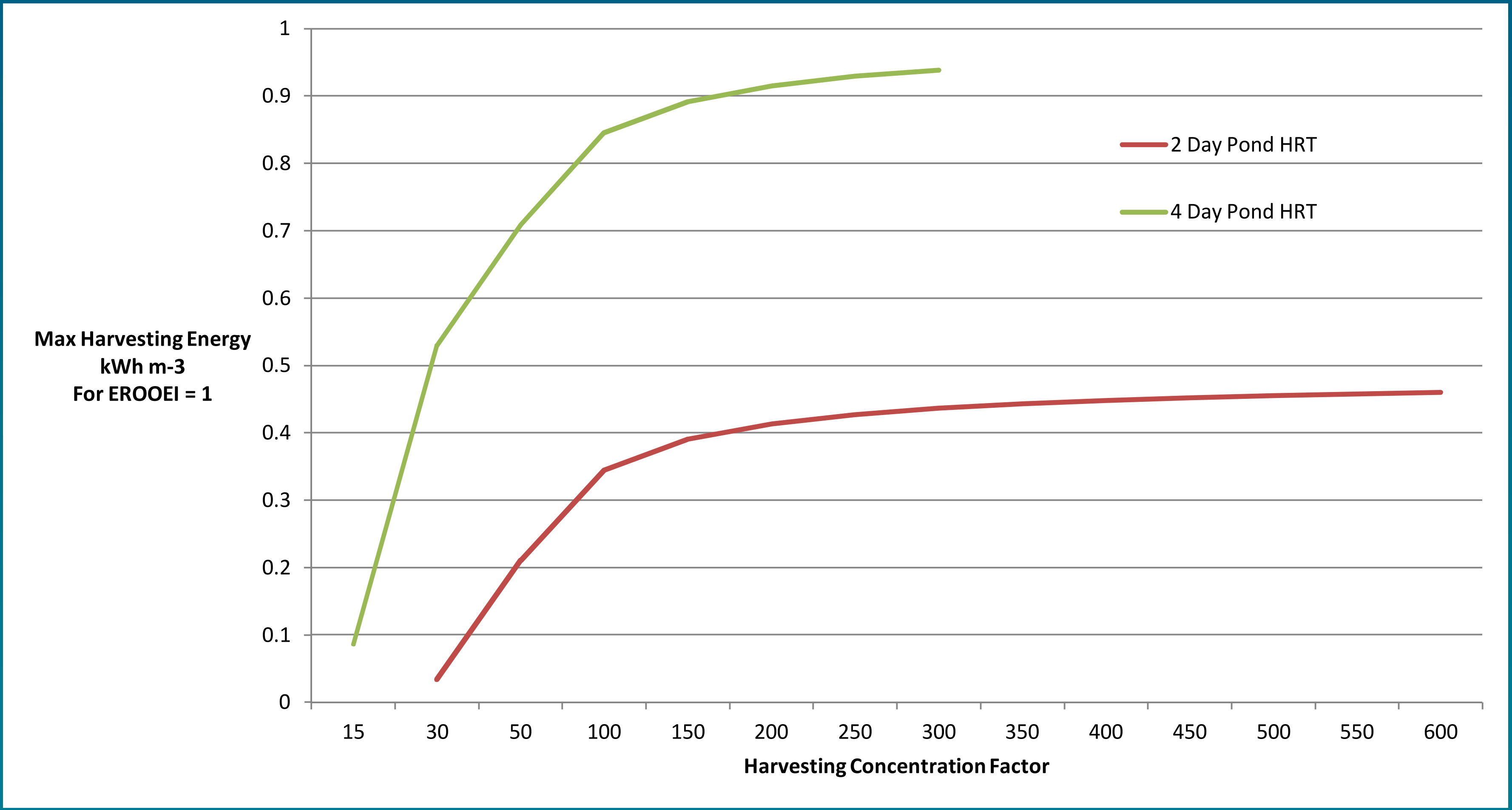
Disc Stack Centrifuges use too much energy

		High	Low
Harvesting			
Harvesting Equipment Energy Input	kWh m^{-3}	1.4	1
Algal Harvesting	%	90	90
Concentration Factor		120	120
Energy Output			
Calorific Value of CH4 production	kWhr^{-1} d^{-1}	842.00	842.00
Energy Input			
Mixing	kWhr^{-1} d^{-1}	43.67	43.67
Total Pumping Energy	kWhr^{-1} d^{-1}	24.20	24.20
Blower Energy for Pond	kWhr^{-1} d^{-1}	28.48	28.48
Harvesting Energy	kWhr^{-1} d^{-1}	2151.09	1536.50
AD Energy			
Heating	kWhr^{-1} d^{-1}	146.19	146.19
Mixing	kWhr^{-1} d^{-1}	34.57	34.57
Total AD Input Energy	kWhr^{-1} d^{-1}	180.76	180.76
Total Operational Energy Input		2428.20	1813.60
Net Energy	kWhr^{-1} d^{-1}	-1586.19	-971.60
Energy Return on Operational Energy Invested		0.3	0.5

Pragmatic case assumptions

Environmental		
Solar Insolation	kWh m^{-2} $year^{-1}$	2000
Photosynthetic Efficiency	%	3
Yield of 20% lipid algae	g m^{-2} day^{-1}	25
Ambient Temperature	° C	20
Pond		
Pond Area	m^2	10017
Pond depth	m	0.3
Pond Fluid Velocity	ms^{-1}	0.3
Gaseous Exchange		
CO2 Concentration in Supply	%	12
Anaerobic Digestion		
% of "Buswell" estimated CH4	%	60
Hydraulic Retention time	days	20
Reactor Temperature	Mesophilic	35
Efficiencies		
Paddlewheel Efficiency	%	50
Gas Transfer Efficiency	%	80
Blower Efficiency	%	80
Pump Efficiency	%	80
Percentage Heat Recovery	%	50
Heater Efficiency	%	80
Mixer Efficiency	%	80

How much energy can be used to harvest algae for AD?



Extracting useful energy from micro-algae

	Utilises entire organic biomass	Requires drying of biomass after harvesting	Primary energy product
Direct Combustion	Yes	Yes	Heat
Pyrolysis	Yes	Yes	Primarily liquid by flash pyrolysis
Gasification	Yes	Yes [b] (conventional)	Primarily Gas
Liquefaction	Yes	No	Primarily Liquid
Bio-hydrogen	Yes	No	Gas
Fuel Cells	Yes	No	Electricity
Bioethanol	No [a]	No	Liquid
Biodiesel	No	Yes [c]	Liquid
Anaerobic digestion	Yes	No	Gas

[a] Currently restricted to fermentable sugars as no large-scale commercial production of fuel bioethanol from lignocellulosic materials

[b] Supercritical water gasification (SCWG) an alternative gasification technology can convert high moisture biomass

[c] No current commercial process for the wet trans-esterification of wet micro-algal biomass

Algal biofuel is not currently viable

- Nearly 70 years of sometimes intensive research on micro-algae fuels and over two billion dollars of private investment since 2000 (Service, 2011) have not produced economically viable commercial-scale quantities of algal fuel and suggests that there are major technical and engineering difficulties to be resolved before economic algal biofuel production can be achieved

SERVICE, R. F. 2011. Algae's Second Try. Science, 333, 1238-39.

~50% of the published LCAs have a net energy ratio less than 1.

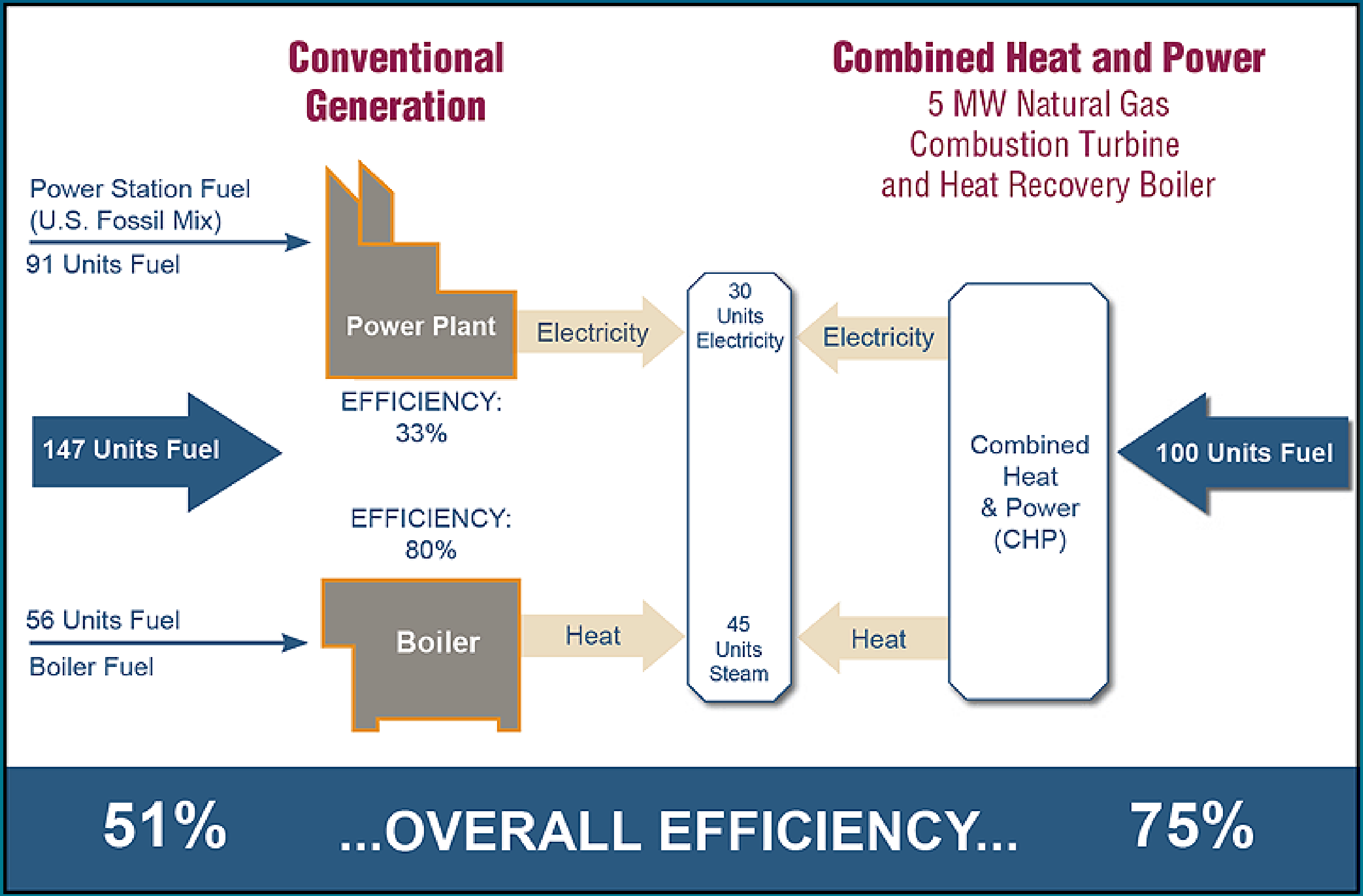
Positive economic/energy studies required

- High value co-products
- Biogas production by Anaerobic digestion
- Use of technology unproven at commercial scale such wet biomass trans-esterification

Anaerobic Digestion of Algae could produce net Energy

			Settlement Centrifugation						Flocculation Centrifugation				
Harvesting						Organic 1 mg l^{-1}			Organic 10 mg l^{-1}			Alum 120 mg l^{-1}	
Algal Harvesting Settlement	%	60	60	60		70	90		70	90		70	90
Concentration Factor Settlement		20	20	20		30	30		30	30		30	30
Algal Harvesting Centrifugation	%	90	90	90		90	90		90	90		90	90
Concentration Factor Centrifugation		30	30	30		20	20		20	20		20	20
Harvesting Equipment Settlement	kWhr day^{-1}	0.005	0.005	0.005		0.005	0.005		0.005	0.005		0.005	0.005
Harvesting Equipment Centrifugation	kWhr day^{-1}	1.4	1	0.35		1	1		1	1		1	1
<u>Energy Output</u>													
Calorific Value of CH4 production	kWhr^{-1} d^{-1}	505.20	505.20	505.20		589.40	757.80		589.40	757.80		589.40	757.80
<u>Energy Input</u>													
Mixing	kWhr^{-1} d^{-1}	43.67	43.67	43.67		43.67	43.67		43.67	43.67		43.67	43.67
Total Pumping Energy	kWhr^{-1} d^{-1}	29.50	29.50	29.50		29.43	29.51		29.43	29.51		29.43	29.51
Blower Energy for Pond	kWhr^{-1} d^{-1}	28.48	28.48	28.48		28.48	28.48		28.48	28.48		28.48	28.48
Harvesting Energy	kWhr^{-1} d^{-1}	72.22	53.78	23.82		52.35	62.59		129.17	139.42		788.70	798.95
AD Energy													
Heating	kWhr^{-1} d^{-1}	20.13	20.13	20.13		23.19	29.23		23.19	29.23		23.19	29.23
Mixing	kWhr^{-1} d^{-1}	4.15	4.15	4.15		4.84	6.22		4.84	6.22		4.84	6.22
Total AD Input Energy	kWhr^{-1} d^{-1}	24.28	24.28	24.28		28.03	35.45		28.03	35.45		28.03	35.45
Total Operational Energy Input		198.14	179.70	149.74		181.95	199.70		258.78	276.52		918.31	936.05
Net Energy	kWhr^{-1} d^{-1}	307.06	325.50	355.46		407.45	558.11		330.63	481.28		-328.91	-178.25
Energy Return on Operational Energy Invested		2.5	2.8	3.4		3.2	3.8		2.3	2.7		0.6	0.8

CHP can be efficient, but ratio electrical to heat energy 0.67



USA Environmental Protection Agency 2013

Algal biogas production has higher demand for electrical energy

			Settlement Centrifugation			Flocculation Centrifugation		
Electrical Energy	kWhr^{-1} d^{-1}	178.0	159.6	129.6	150.2	161.9	150.2	161.9
Heating	kWhr^{-1} d^{-1}	20.1	20.1	20.1	23.2	29.2	23.2	29.2
Ratio		8.8	7.9	6.4	6.5	5.5	6.5	5.5

What do we do with the excess heat energy?


pharmaceuticals
companies
government
process
public
effluent
food
production
treatment
high-value
security
biofuel
CO2
GHG
low
pilot
technological
aquaculture
data
world
algae
biofuels
fuel
plants
research
funding
subsidies
wastewater
awareness
biomass
markets
products
cheap
harvesting
viable
policies
carbon
energy
scale
nutraceuticals

Current examples of non-fuel uses of Micro-algae

- β-carotene produced from *Dunaliella*
- Lina Blue, a blue Phycobiliprotein food colourant, produced from *Spirulina*
- Docosahexaenoic acid (DHA), a polyunsaturated omega-3 fatty acid, produced by heterotrophic culture *Crypthecodinium cohnii*
- Sulphated polysaccharides for cosmetic products from *Porphyridium*
- Food and feed additives for the commercial rearing of many aquatic animals are produced from a variety of micro-algal species.

Namibia 2008 Pure Energy Fuels

Van Eck coal powered station, Windhoek

Micro-algal Biofuel

Walvis Bay

Micro-algal Food Supplements

Pure Energy
Fuels Ltd.

What were we looking for

- Carbon dioxide supply;

1.65 to 2.2 kg CO_2 per kg of dry algae

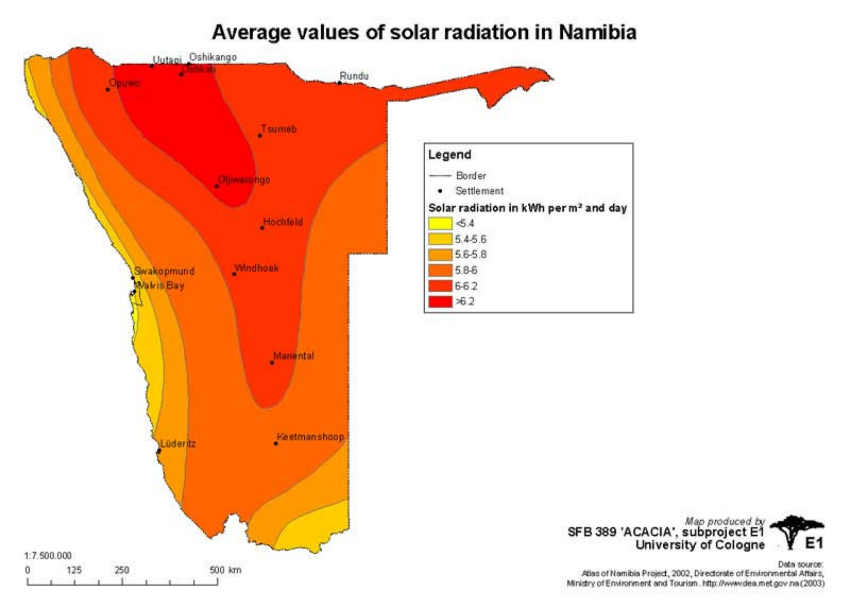
- Water
- Land
- Nutrients - high content of both N and P relative to land plant

N - 5 to 12 % P - 0.3 to 1 %

- Political stable and supportive

Favourable Climate

High Solar Insolation

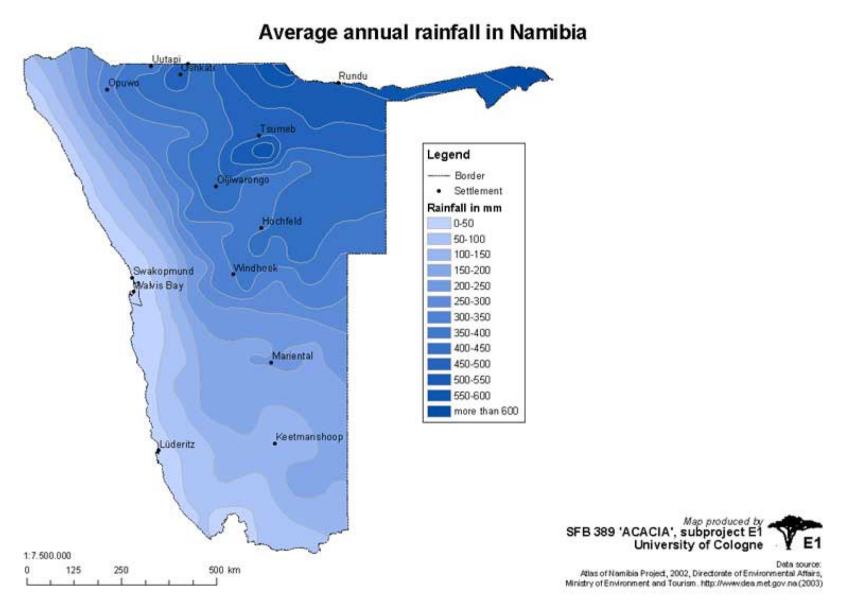


Average values of solar radiation in Namibia

Map produced by
SFB 389 'ACACIA', subproject E1
University of Cologne

Data source:
Atlas of Namibia Project, 2002, Directorate of Environmental Affairs,
Ministry of Environment and Tourism. http://www.dea.met.gov.na (2003)

Low Rainfall



Average annual rainfall in Namibia

Map produced by
SFB 389 'ACACIA', subproject E1
University of Cologne

Data source:
Atlas of Namibia Project, 2002, Directorate of Environmental Affairs,
Ministry of Environment and Tourism. http://www.dea.met.gov.na (2003)

Salt Ponds Walvis Bay, Namibia. Courtesy NASA.

http://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=ISS018&roll=E&frame=6878&QueryResultsFile=123668532621801.tsv

Dunaliella Salina

- Grown in highly saline water for the production of β-carotene.
- Occurs naturally in salt pans

Courtesy of Cognis Australia Pty Ltd

Could *Dunaliella* be grown as a co-product of open pan salt production?

Potential Capital Expenditure, Income & Profit from *Dunaliella salina*

	Mixed Ponds	Unmixed Ponds	Salt Ponds	
Pond Costs Construction & Energy				
Target production Metric Tons	300	300	300	
Yield Metric Tons per Hectare per Year	6	1.5	1.5	
Yield g m^{-2} per day	1.6	0.4	0.4	
Total Pond Area Hectares	50	200	200	
Pond Construction Cost Per Hectare	$100,000	$25,000	$0	
Pond Construction 300t Algal Ponds	$5,000,000	$5,000,000	$0	
Power Mixing & Aeration KW	5.5	0	0	
Energy Cost 300t Algal Ponds	$410,494	$0	$0	0.12 £/KWhr
Harvesting & Dryer Costs				
Capital Cost	$5,250,000	$5,250,000	$5,250,000	
Energy Cost Harvesting & Drying per year	$400,000	$400,000	$400,000	
Total Capital Cost Excluding Land	$10,250,000	$10,250,000	$5,250,000	
Land Cost 300t Algal Ponds	$500,000	$2,000,000	$0	10000 $/hectare
Land Cost Access etc.	$100,000	$100,000	$0	10 hectare
Land Plant	$20,000	$20,000	$20,000	2 hectare
Total Land Cost	$620,000	$2,120,000	$20,000	
Total Capital Cost	$10,870,000	$12,370,000	$5,270,000	
Projected Income and Expenditure				
Target production Metric Tons	300	300	300	
Sale Price per Kg	$20	$20	$20	$20
Total Income	$6,000,000	$6,000,000	$6,000,000	
Depreciation (excluding land)	$1,025,000	$1,025,000	$525,000	10 years
Interest	$543,500	$618,500	$263,500	5% Cap inc Ld
Energy	$810,494	$400,000	$400,000	
Labour	$1,230,000	$1,230,000	$630,000	12% Cap ex Ld
Sundry (Maintenance etc.)	$410,000	$410,000	$210,000	4% Cap ex Ld
Total Expenditure	$4,018,994	$3,683,500	$2,028,500	
Plant Net Profit	$1,981,006	$2,316,500	$3,971,500	
% Annual Return on Investment inc Land	**18%**	**19%**	**75%**	

Micro-algal Biorefining

- Co-production of a spectrum of high value bio-based products (food, feed, nutraceuticals, pharmaceutical and chemicals) and energy (fuels, power, heat) from biomass that could allow the exploitation of the entire micro-algal biomass produced.

Biorefineries should be sustainable

- The energy inputs required by a biorefinery should be met by bioenergy produced from the refinery .

Vertical Biorefinery

- produces a variety of products from a single biomass source.
- *Dunaliella* could provide the biomass for a biorefinery – producing high value β-carotene and glycerol

The microalgal species found in open salt pan production systems vary throughout the process with changing salt concentration.

The variety of microalgal species in the various stages of salt production might provide additional microalgal biomass feed stocks that may yield an additional range of high value products.

Horizontal Biorefinery

- The exploitation of changing microalgae with increasing salt concentration for a variety of end products may be termed a horizontal biorefinery.
- *Porphyridium*, a marine red microalga, currently cultivated in Israel for cosmetic products, could be grown in the initial marine water feed ponds to produce sulphated polysaccharides, polyunsaturated fatty acids, antioxidants and carotenoids

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Thank you

Questions Please