June 2004 ECN-RX--04-036

MICROALGAL MASS CULTURES FOR CO-PRODUCTION OF FINE CHEMICALS AND BIOFUELS & WATER PURIFICATION

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Presentation CODON Symposium "Marine Biotechnology; An ocean full of prospects ?"
25th March 2004, Wageningen

Revisions		
A		
B		
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MICROALGAL MASS CULTURES FOR CO-PRODUCTION OF FINE CHEMICALS AND BIOFUELS & WATER PURIFICATION

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Mass cultures of microalgae are suitable for production of renewable chemicals and fuels *and* for CO_2 fixation *and* water purification. The combination of production of renewable materials with environmental applications is one of the hallmarks of microalgal culture. It supports sustainability and process economy. At the same time the combination poses challenges to process development.

In the project, a novel type of cultivation system is being developed. It is composed of an array of ‘bubble column’ type photobioreactors for inoculum production of the targeted algal species, which is fed continuously into a cascade-type open cultivation system with a number of basins placed in series. In principle this system allows large-scale, selective cultivation of a broad range of algal species at moderate costs. Outdoor results for *Monodus subterraneus* and *Chlorella fusca* show that the bubble column provides a robust production system, allowing mono-algal cultivation for periods exceeding 9 months. Cultivation of two microalgal species (the green alga *Chorella fusca* and the cyanobacterium *Synechococcus sp.*) was tested in an experimental integrated system outdoors. Modifications were identified including improved CO_2 supply and improvement of the hydraulic mixing regime in the open basins. Lab scale experiments have shown that algal cultivation with effluents for substrate is possible and suits well the target of removal of N and P compounds from the wastewater.

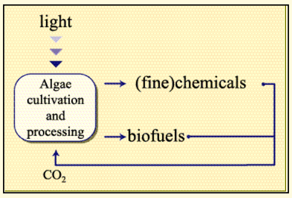
Harvesting is a crucial issue due to the relatively high investment costs of equipment and the need for effective algal biomass removal and concentration with limited energy use. A range of technologies was tested. Flotation followed by mechanical dewatering and final sand filtration or membrane filtration shows satisfactory performance with respect to costs and energy use. The harvested algal biomass is intended as a feedstock for extraction of high value fine chemicals (e.g. colorants, bioactive substances) with the residues used for production of biofuels. For energy conversion of the residual biomass both thermal conversion by combustion or gasification and anaerobic digestion to methane were evaluated. Highlights from the project and issues for further development will be discussed.

1) This project is supported with a grant of the Dutch Programme EET (Economy, Ecology, Technology) a joint initiative of the Ministries of Economic Affairs, Education, Culture and Sciences and of Housing, Spatial Planning and the Environment. The programme is run by the EET Programme Office, a partnership of Senter and Novem.

Microalgal mass cultures for co-production of fine chemicals and biofuels & water purification (EET K 99005)

Introduction

- Technology development
- Economics
- Ecology
- Perspectives and further R&D



J.H. Reith, ECN Unit Biomass

CODON symposium, *Marine Biotechnology*, 25 March 2004

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Characteristics algal mass cultures

- high areal productivity**:** efficient use of sunlight and nutrients photochemical η_{PAR} 5-10% vs. max. 2.5 % for land based crops
- range of fine chemicals and bulk products
- cultivation in aquatic environment offers perspectives for
  - ⇨ direct fixation of CO_2 from flue gas>>"credits"
  - ⇨ water purification for recycle: removal of nutrients NH_4^+,$NO_3^-$$PO_4^-$ from effluents < 10's µg/l water = bulk co-product with increasing market value

⇨ **Potential multifunctionality = key to economic profitability and sustainability**

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Productivity in the Netherlands (53°N)

NL climate is suitable for algal culture

Crop	Productivity	Energy
	ton/ha.year	GJth/ha.yr
Winterwheat (seed + straw)	11	170
Sugarbeets (root + leaves)	20	370
Rapeseed (seed + straw)	9	180
Willow	10	180
Miscanthus	16	270
Microalgae:		
- current η_{PAR} 5 %	**30**	**600**
- optimized η_{PAR} 10 %	**60**	**1200**
- theor. Max. η_{PAR} 20 %	**ca. 120**	**2400**
Wind turbine (6m/s)		(eq) 1440
PV (15%; 1/3 occupation)		(eq) 5130

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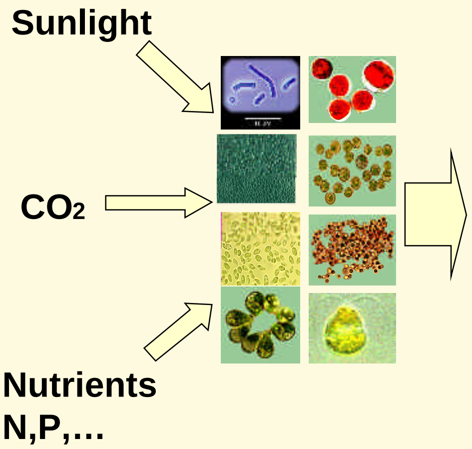
Wide range of biomass applications



> 30.000 species

Source of fine chemicals & bioactive substances
- carotenoids / phycobiliproteins
- ω-3 & ω-6 fatty acids
- polysaccharides
- antioxidants
- bactericides, fungicides
- plant growth promotors

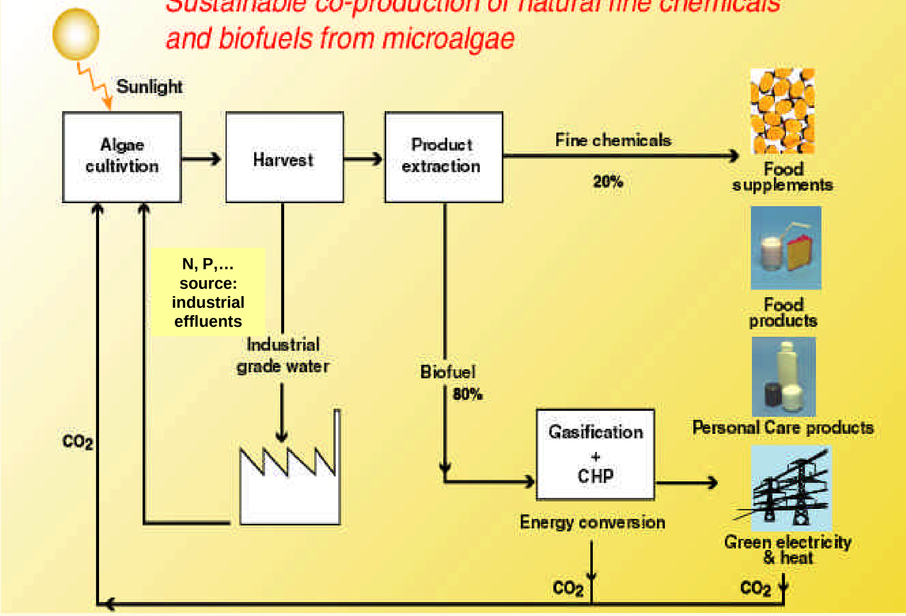
Feed / aquaculture
[proteins, PUFA, antioxidants]

Soil conditioners / agrochemicals
[growth promotors, fungicides, polysacch.]

Energy carriers
biodiesel, hydrocarbons, methane, ethanol, E + H

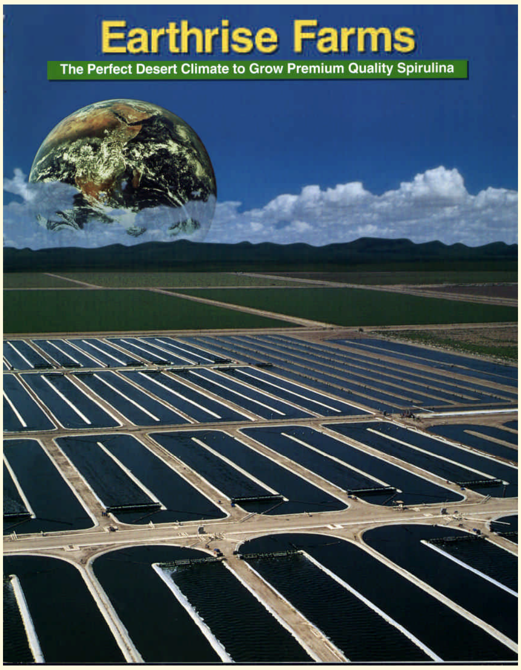
EET Project K99005

Sustainable co-production of natural fine chemicals and biofuels from microalgae



Cultivation/harvesting	Processing	Energy conversion	Product application
Universiteit van Amsterdam	KLB-TUDelft	Techno Invent BV	Numico Research BV
Wageningen University	A&F	ECN Biomass	CSK food enrichment BV
ECN Biomass		Essent Energy BV	Royal Sanders BV
IVAM Environmental Research BV			

High Rate Algal Pond (HRAP)



Large-scale commercial use

- easy scale-up
- low investment costs
- low energy requirement

→ low selectivity: contamination + long residence time

→ photochemical efficiency ~5%

→ low biomass density

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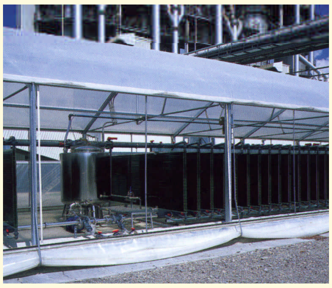
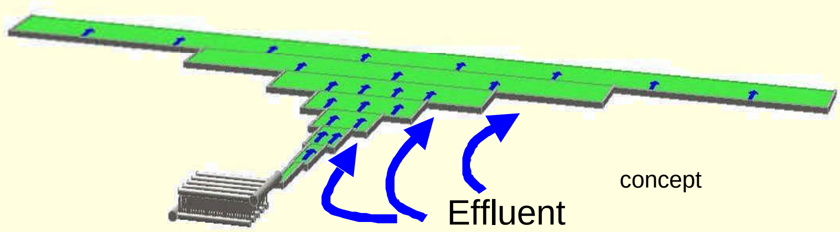
(Semi)closed photobioreactors

Commercial systems up to 1 ha
- good selectivity & process control
- high(er) biomass density
- high(er) areal productivity:
  photochemical efficiency 10 -15%
- ➔ engineering & scale up
- ➔ energy demand relatively high
- ➔ high investment costs

Cultivation system* development



Concept:
- bubble column reactors for continuous inoculation
- open cascade of increasing surface area>> supply effluents
- “once through” hydraulic regime>> no backmixing>>
  >> no build up of contaminants (< 0.02%)
- adequate mixing required

➔ large-scale selective cultivation AND water purification at acceptable cost

*) European patent 1272607

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Development bubble column photobioreactor

- design, operation + modelling indoors: WU
- operation + modelling outdoors: ECN

• robust cultivation system; low maintenance

• stable long-term uni-algal production (> 1 yr)

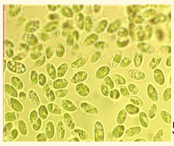
• year round cultivation with low T heat feasible

• Yield independent of algal concentration

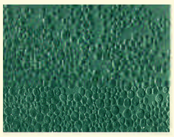
Y=0.48 g E^{-1} (4.8% PAR) *M. subterraneus >>30 tons/ha.yr*

Y=0.88 g E^{-1} (9.9% PAR) *C. fusca >> 60 tons/ha.yr*

• models for simple process control



5 µm



3-5 µm

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Experimental cultivation system (UvA, IVAM)

• operational strategy determined

• productivity estimate : ~ 40 ton d.w./ha.yr

• improve hydraulic regime & CO_2 transfer

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Lab-scale results (UvA)

- cultivation principle proven (P.O.P.)
- good N+P removal effluents sugar production & brewery
- thermophilic cyanobacteria show good perspective (selectivity, product stability, use of waste heat)
- screening program fatty acids (EPA), polysaccharides, bio-actives
- modification of fatty acid spectrum by growth conditions

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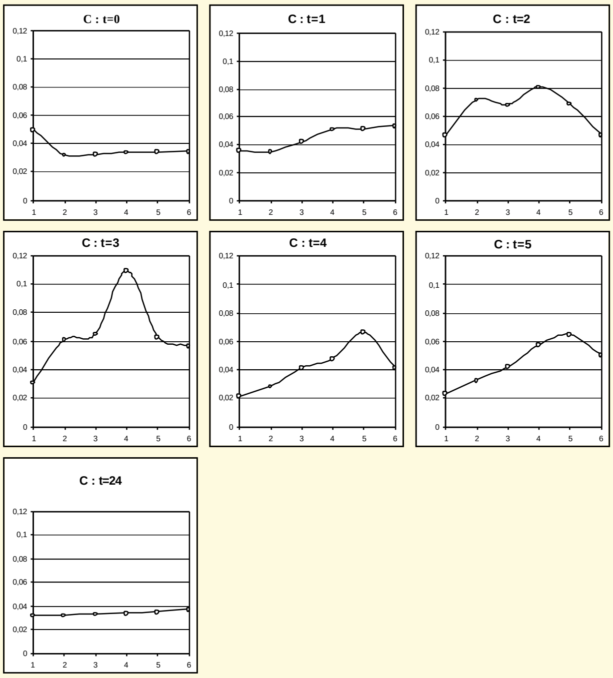
P.O.P cultivation principle (UvA)



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Harvesting and final water conditioning
(IVAM, ECN)

Requirements

1. concentration + dewatering 0.03 w% >> 10 w%
2. large-scale feasibility
3. industrial grade water quality (=residual algae<6 mg/l)

Test program (lab/pilot) with a range of techniques

- flotation + centrifugation + sand bed filtration
  optimal configuration (e: 0.4 kWh/kg & cost 0.6 Euro/kg)
- UF alternative for high(er)water quality
- low-cost flocculant with GRAS status identified
- future perspectives:
  - membrane technology
  - bioflocculation ?

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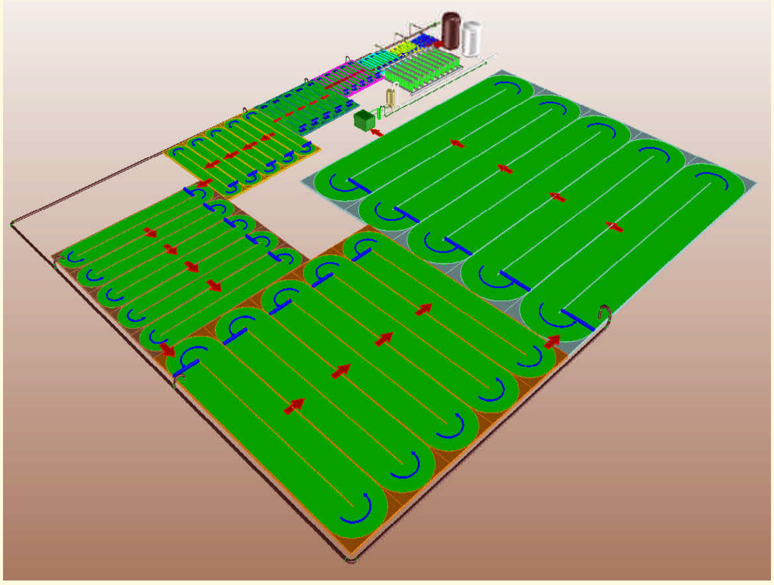
Integral system (concept)



- system simplification; cost- and energy reduction

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Extraction & purification of fine chemicals

Focus: ω-fatty acids (EPA) & colorants

A&F:

- "tailor-made" disruption/extraction protocols
- extraction methods using food-grade solvents
- good stabilization of colorants with carrier materials

TUDelft:

- EPA purification gradient Simulated Moving Bed chomatography

→ processing designs for EPA and colorants

Follow-up:

- scale-up, increase extraction efficiency, cost reduction hardware and biomass
- increase of product concentration

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Screening & application

Numico, CSK food Enrichment, Royal Sanders

- No "hits" bio-active products
  >> screening volume small (10 sp.)
- Larger screening program (HTS) recommended
- EPA: potential longer term interest
- Good prospects stabilized colorants in food & cosmetics
- Economic obstacle: admission procedures (EU) for new food and bio-active ingredients

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Energy conversion of biomass residues

ECN, Essent,Techno Invent, LeAF

- limited energy potential: 4 MWth for 2 products
- all residues suitable for co-firing>> positive market value
- drying system using waste heat> 5-fold cost reduction

Integrated e-conversion at processing plant:

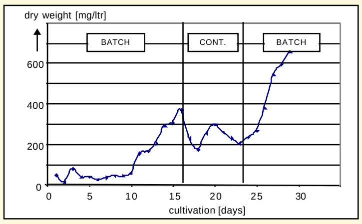
- “stand-alone” gasification/combustion feasible on larger scale
- small-scale anaerobic digestion feasible
- conversion “on site” provides 20-50% of energy for processing

Economy

- current design produces industrial grade water (0.4 €/m3) and biomass (2-4 €/kg) at realistic market prices, POT: 2-4 yrs
- investment cultivation>> biomass cost major cost drivers
- EPA cost comparable to biotechnological oils
- colorants show good economic potential (food, cosmetics); production at competitive price feasible

CO_2 biofixation & water purification

Integration at industrial locations



Growth of Chlorella with flue gas 10 vol% CO_2
& condensate beet sugar production NH_4^+ 30 mg/l

- active CO_2 uptake/ NH_4^+ removal >99 %
- effective N + P removal brewery effluents

CO_2-from flue gas (10%) or fermentation off-gas (75%)

water purification for re-use feasible
- N + P removal high volume effluents food- & agro-industry
- energy and cost savings & ecological benefits

- areal estimate water recycle food and agro-industry

- 2000 ha (NL): 200 Mm^3/water + 60.000 ton biomass
- 23.000 ha (EU-15)

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Ecology (IVAM & ECN)

- energy balance biomass production

electricity for cultivation and harvesting	171	kWe
energy savings water purification	79	kWe
Net e-use	92	kWe
Net electricity use/year (6480 hours)	596,160	kWh/yr
primary energy (/ 45%)	4769	GJth
primary energy in biomass (300 ton)	6600	GJth

Reduce energy use/optimize water purification

- screening LCA for 2 product chains >>
  positive ecological effect (6-8 environmental parameters)

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Perspectives and follow-up R&D

Focus on cultivation system

- proof-of-concept on pilot scale, industrial location
- system simplification; cost- and energy reduction
- optimize biomass productivity and water purification
- medium value applications whole biomass
- colorants

High Throughput Screening

- productivity & product content (bio-active products,...
- technology development required

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Programmabureau E.E.T.: B. ten Brink & W. Broens.

economieecologietechnologie

This project is supported with a grant of the Dutch *Programme E.E.T. (Economy, Ecology, Technology)* a joint initiative of the Ministries of Economic Affairs, Education, Culture and Sciences and of Housing, Spatial Planning and the Environment. The programme is executed by the E.E.T. Programme Office, a partnership of Senter and Novem.

Report (in Dutch) will be available at

- www.eet.nl
- www.ecn.nl

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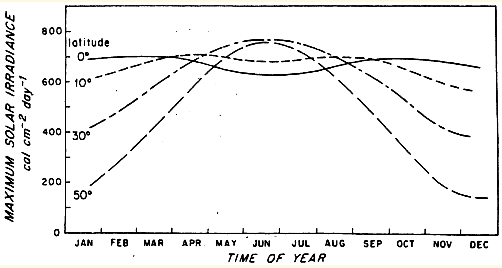
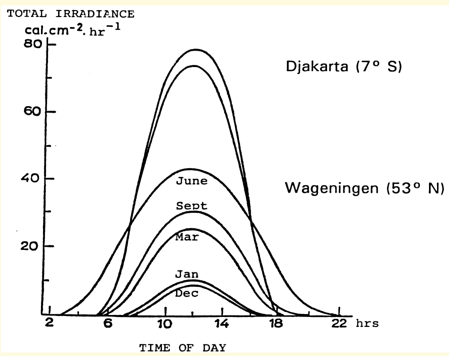
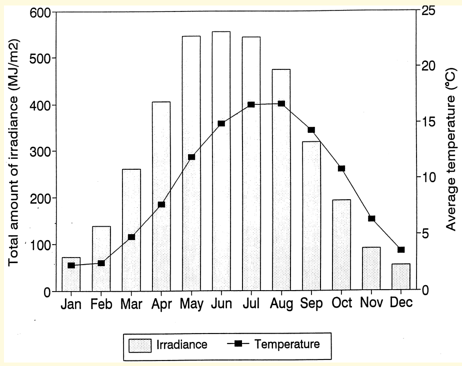
Climate in the Netherlands







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Productivity~ latitude

Latitude	Solar irradiation at ground level	Productivity (10% PAR)	Maximum productivity (23% PAR)
Degrees	GJ/m2/yr	ton d.w. /ha.yr	ton d.w. /ha.yr
0º	7,18	136	312
20º	6,82	129	296
Athens (37º)	5,65	107	246
Amsterdam (52º)	3,6	68	156
Ostersund (63º)	3,1	58	134

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Optimizing productivity

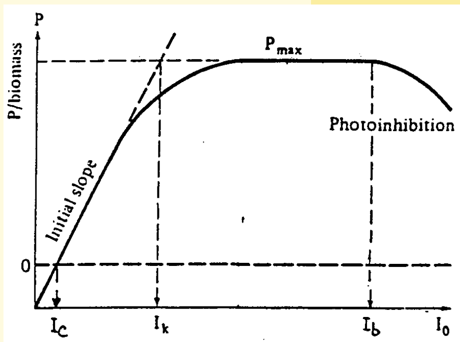
Photosynthesis reaction:

$CO_2 + H_2O$ ® $(CH_2O) + O_2$

η_{max} $PAR_{400-700\ nm}$ = 23 %

Losses:

- light saturation & photo-inhibition
- photo- and dark respiration



R&D challenges:

- >>"light limitation" in full sunlight
- reduce respiration

Approaches:

reactor geometry

mixing regime / L-D cycli

operational density

truncated antennae