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INTEGRATED BIOFUEL FACILITY: CARBON DIOXIDE CONSUMPTION & POWER GENERATION

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Outline

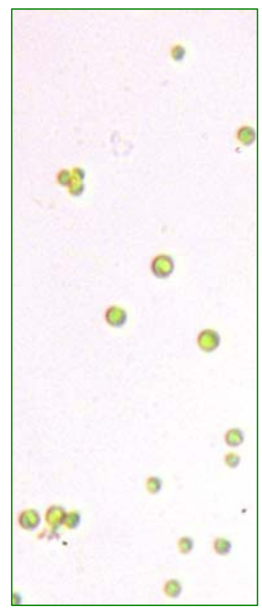
- Project background
- Growth kinetics of *Chlorella vulgaris*
- Novel photobioreactor design
- Industrial implementation:
  - Supplementary technology
    - Photosynthetic biocathode and coupled microbial fuel cell
- Integrated biofuel facility design
- Future directions

Background: CO_2 and the environment

- Greenhouse gases: 740 megatonnes annually
  - 79% is CO_2
- Climate change
- Remediation
  - Biological methods: microalgae

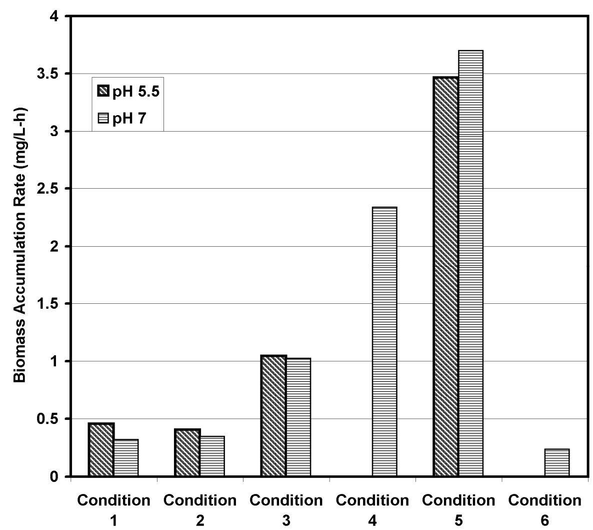
Background: microalgae

- Microalgae
  - Photosynthetic
    - CO_2 fixation
      - 10 x rate of temperate forest
  - Biotechnology
    - biomass and valuable by-products
- *Chlorella vulgaris*
  - Green freshwater eukaryotic species
  - High growth rate, ease of cultivation



Growth kinetics: *C. vulgaris*

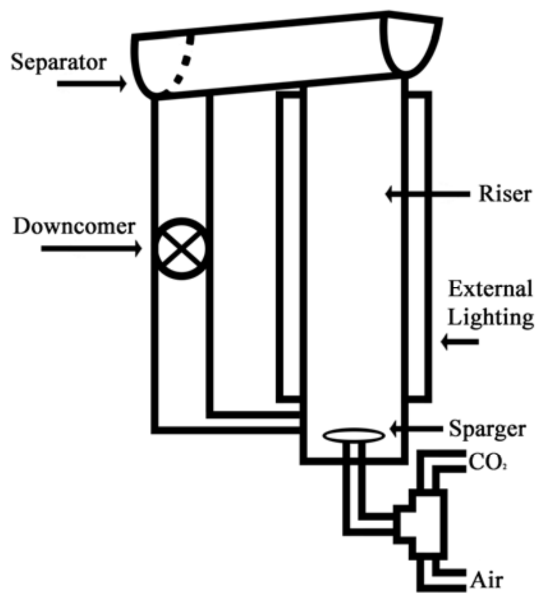
- Maximum biomass accumulation rate
  - 32.3 mW
  - 10% CO_2 enrichment of feed air
- Linear growth curve
  - Light limitation
- Yield: 0.51 g biomass / g CO_2



Effects of environmental parameters on growth rate of *C. vulgaris*. Conditions: 1: 0.037% CO_2 in Air, Light = 6.0 mW; 2: 10% CO_2 in Air, Light = 6.0 mW; 3: 0.037% CO_2 in Air, Light = 32.3 mW; 4: 5.0% CO_2 in Air, Light = 32.3 mW; 5: 10% CO_2 in Air, Light = 32.3 mW; 6: 20% CO_2 in Air, Light = 32.3 mW.

Novel Photobioreactor Design

- External loop airlift photobioreactor (ELAPB)
- Two distinct regions
- Increased light penetration
- Consistent mixing
  - Reduction in shading of cells from light source
- Mass transfer of CO_2



Schematic of External Loop Airlift Photobioreactor.

Novel Photobioreactor Design

- External riser lighting
  - Miniature white LED strips
- Dark downcomer
  - Resting stage in cycle
  - ½ volume of riser
- Tray separator
- 3 L

Novel ELAPB in Operation.

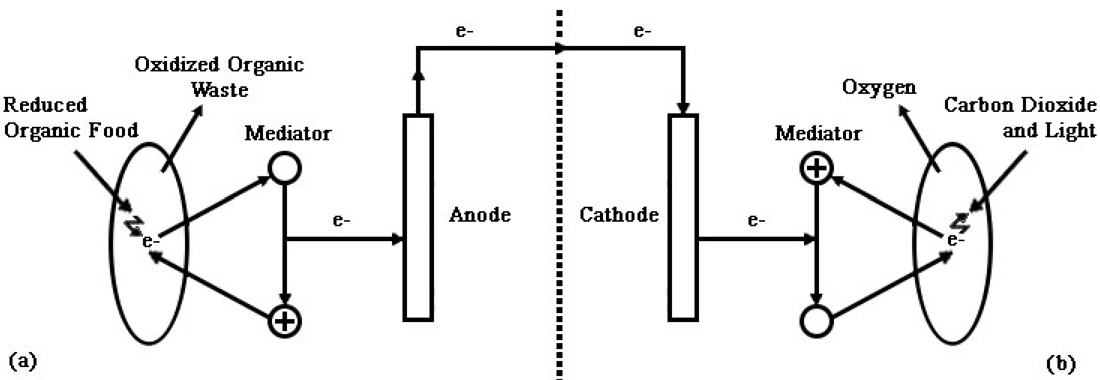
Novel ELAPB: Growth Study

- Batch study of biomass accumulation over time
  - Light intensities (measured at inner reactor wall)
    - 0.027 W – 0.43 W
  - CO_2 enrichment of inlet air
    - 0.038 % to 15 %
  - Specific growth rates
    - 0.01 h^{-1} – 0.04 h^{-1} .
  - Non-linear growth curves
- Data is used for development and validation of growth model

Implementation: by-products and supplementary technologies

- Microbial fuel cell
  - Electrochemical energy conversion device
  - Oxidation – reduction reactions within living microorganisms
- Novel photosynthetic biocathode in a microbial fuel cell (MFC)
  - Possible to use *C. vulgaris* cultivation as direct electron acceptor in a MFC
  - Power generation with CO_2 consumption
  - Couple to a bioanode to create a completely microbial fuel cell

Coupled Photosynthetic MFC



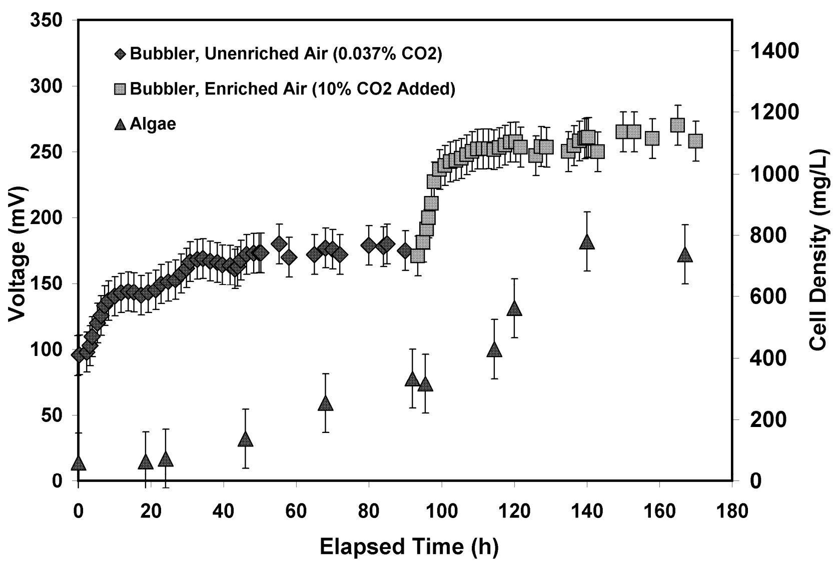
Schematic of Electron Flow in the Completely Biological MFC: (a) anodic release of electrons by consuming organic compounds, (b) cathodic capture of electrons by photosynthetic growth on CO_2

Coupled MFC in Operation

MFC Feasibility Study Results

- Loading study:
  - Maximum power density 1 mW/m^2 at 90 mV and 5000 Ω, 40 μA
- Supplemental glucose addition – anode
  - Increased output by factor of 3
- 10% CO_2 enrichment of feed air – cathode
  - Increased output by factor of 1.7
- Yeast >> microalgae

Carbon Dioxide Enrichment of Feed Air



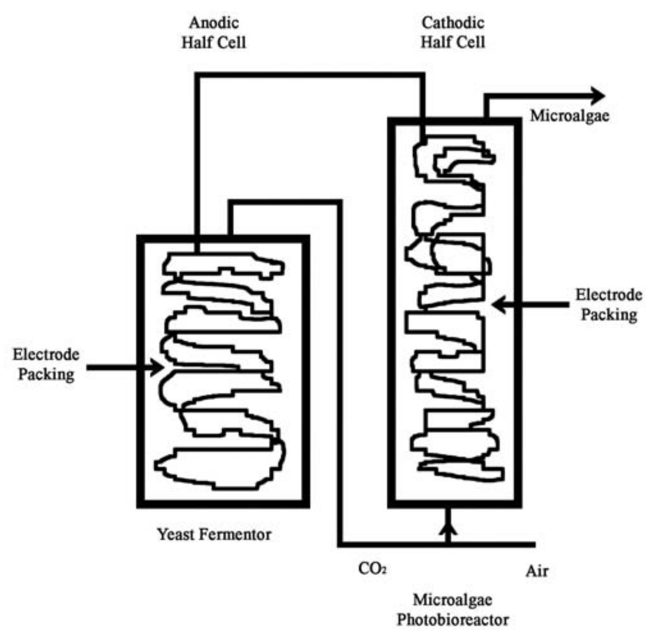
Effect of CO_2 Addition on the Microalgae Cathodic Half Cell

Implementation: Bioethanol Plant Integration

- Integrated Biofuel Facility with CO_2 Consumption and Power Generation
  - Bioethanol Facility
  - Microalgae Cultivation in ELAPBs
    - CO_2 consumption
    - Revenue from by-products
      - Biodiesel from algae oil
      - Feed supplement from biomass
    - Coupled MFCs from power generation

How is the plant integrated?

- Existing yeast fermentation tanks
  - Bioethanol
  - Anodic half cells
- Integrated novel ELAPBs
  - Photosynthetic cathodic half cells
  - Continuous operation
  - Sequestration of CO_2 from fermentation
  - Microalgae production
    - biodiesel (oil), animal feed supplement (biomass)



Economic Feasibility: Integrated Biofuel Facility

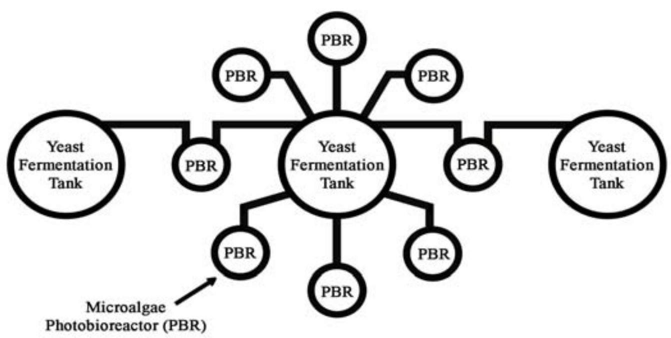
- Design method for economic feasibility:
  - Capital and operating costs, taxation, depreciation, loan repayment, revenue from algae by-products and power generation, value of CO_2 emission recovery (carbon credits)
- Maximize net present worth (NPW) or internal rate of return (IRR)
- Total number and column dimensions of ELAPBs
  - Each ELAPB creates a coupled MFC

Economic Feasibility: Integrated Biofuel Facility - Design #1

- Batch Bioethanol Facility – 130 million L / y
  - 23 stirred tanks (65% operation at any one time)
  - 48 hour batches
- ELAPB cathode dimensions:
  - 50 m height,1 m diameter, 39.3 m^3 volume
  - Continuous operation
- Total number of ELAPBs in plant: 120
  - 8 per fermentor in use
  - Multiple connections

Economic Feasibility: Integrated Biofuel Facility - Design #1

- 100 % CO_2 consumption
- Biomass sold for off-site oil processing
- NPW (rate of return 10%)
  - $ 30 million (20 year plant life)
- $15 / tonne



Multiple ELAPBs surrounding a single existing fermentation tank.

Economic Feasibility: Integrated Biofuel Facility – Design #2

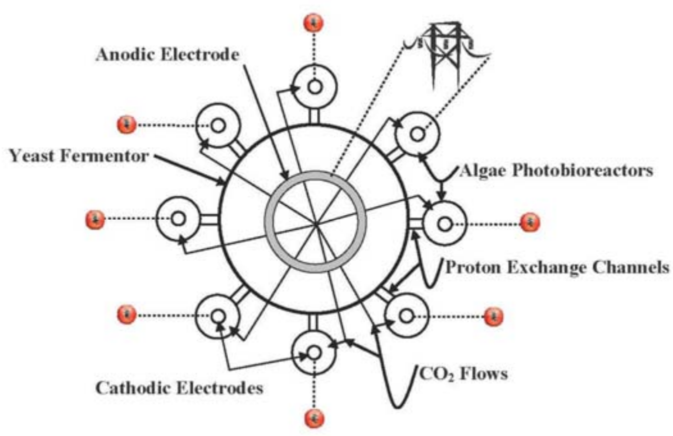
- Continuous Bioethanol Facility – 130 million L / y
  - 3 stirred tanks
- ELAPB cathode dimensions:
  - 30 m height,1 m diameter, 23.5 m^3 volume
  - Continuous operation
- Total number of ELAPBs in plant
  - 69 (23 per fermentor)

Economic Feasibility: Integrated Biofuel Facility – Design #2

- 40 % CO_2 consumption
- Oil extraction and feed supplement processing on-site
- IRR: 9.9%
  - Carbon credits:

  $15 / tonne

  ⟶ $100 / tonne



Location of photobioreactors around a yeast fermentor.

Future Directions

- Experimental Testing
  - Scale-up
  - Implementation schemes
  - Further by-product and MFC studies
    - Oil (biodiesel)
    - Other microalgae species
    - Biocathode and MFC design
- Other Implementation Designs
  - Flue gas from power plants – 10-13% CO_2

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QUESTIONS?