Algal-Microbial Desalination System for Clean Energy, Water and Biomass Production

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Wastewater Treatment

By conventional aerobic treatment

- Low-strength wastewaters such as domestic wastewater
- High capital expenditure
- Considerable operational and energy consumption costs
- Aeration energy demand of about 0.5 kWh/m^3(up to 60% of total), amounting to an energy use of the order of 30 kWh per capita per year
- Large amounts of excess sludge (around 40%), requiring an appropriate treatment and disposal

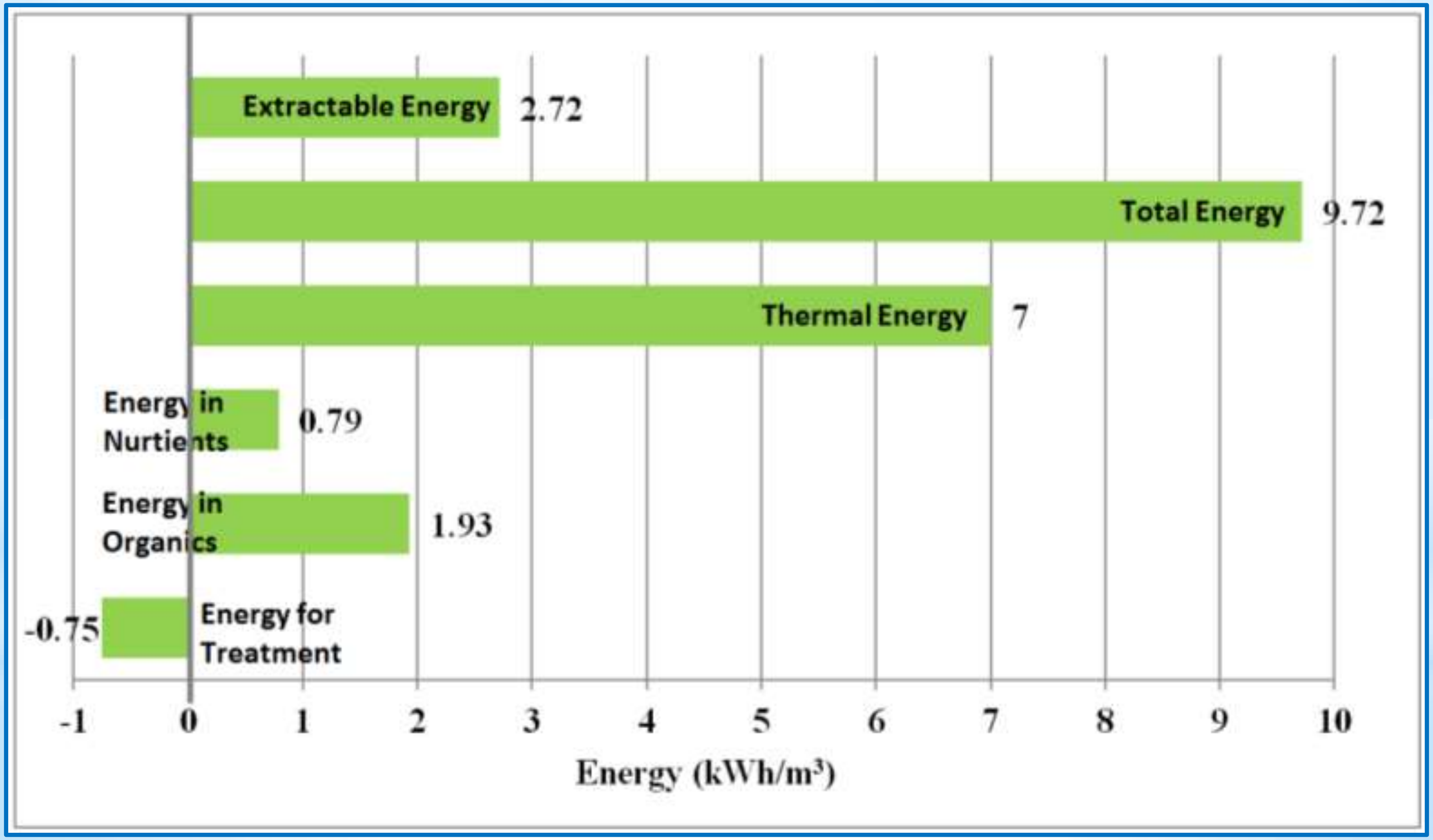
US Energy Consumption

- U.S. consumes about 27, 230 trillion (10^{12}) BTUs of petroleum products in the transportation sector ($28.7x10^{12}$ MJ/year) with more than 60% being imported from foreign countries
- Water and Wastewater treatment accounts for about 4 - 5% of the U.S. electrical energy load, similar to that in other developed countries
- About $ 25 billions are spent for water and wastewater treatment annually in U.S.
- Over next 20 years, water and wastewater treatment infrastructure will require > 2 trillions for building, maintaining, and operating these systems

Wastewater: Energy & Water Resource

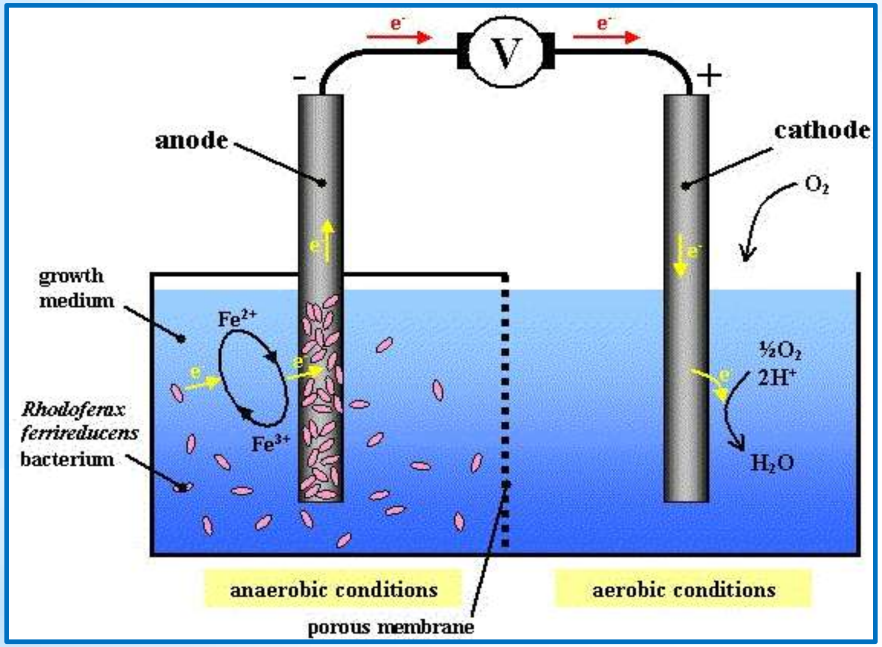
- Wastewater contains up to 10 times energy needed to treat
- Wastewater has the substrate required for microbial electricity generation
- Treated wastewater can be reused for many other purposes as “NEWater”

Energy in Wastewater



(Mc Carty et al., 2011)

Microbial Fuel Cells



Applications

Wastewater treatment
Hydrogen production
Nutrient removal
Electricity production
Other chemical degradation and separation

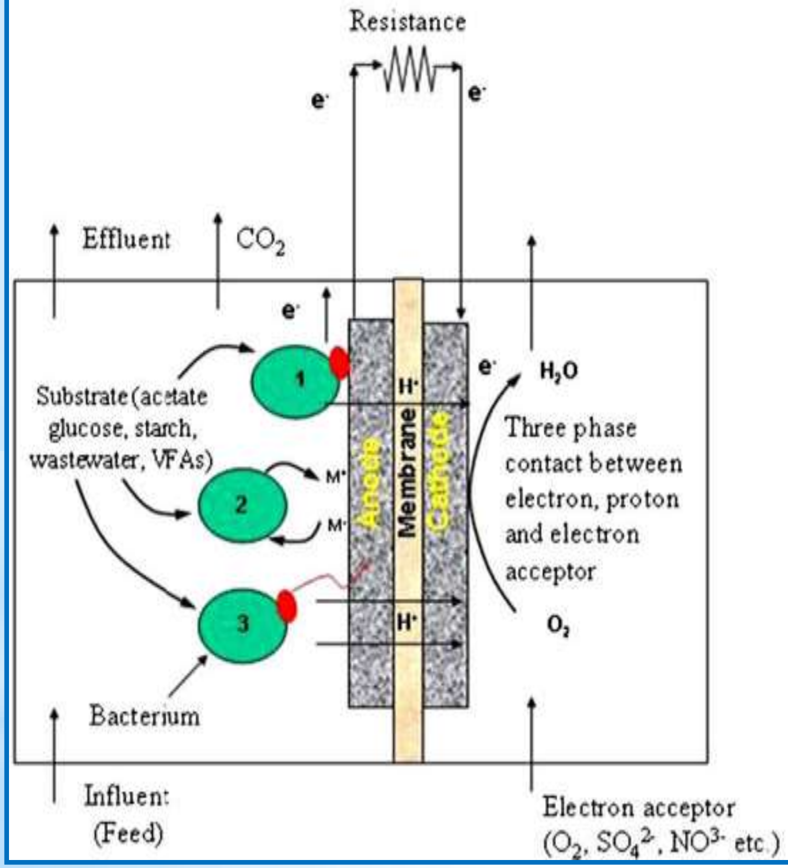
Glucose as an example substrate :

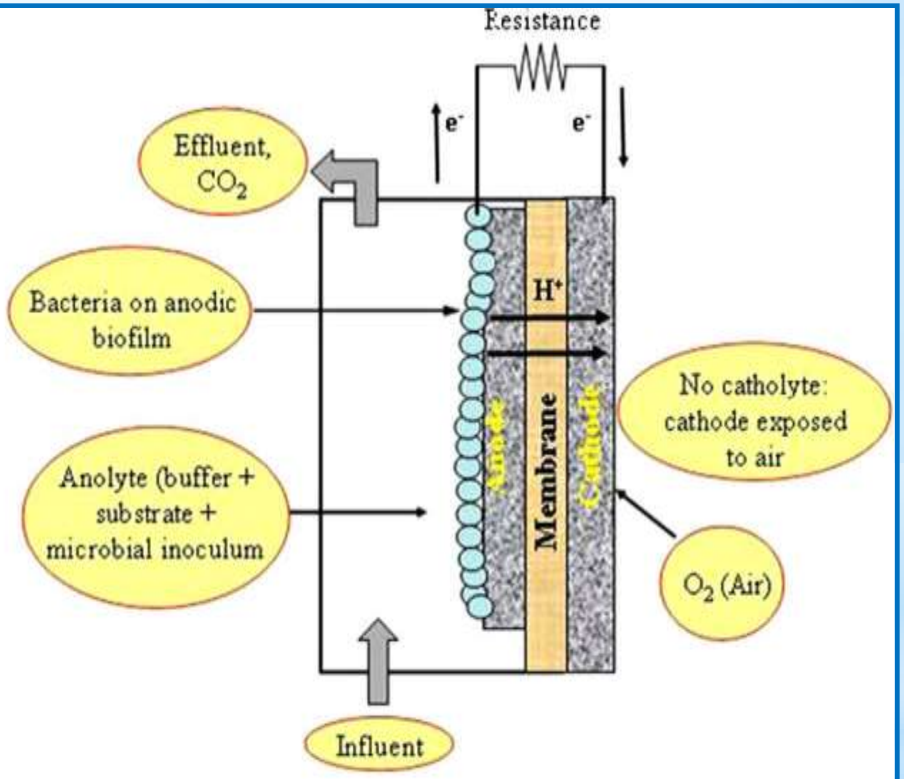
- $C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2C_2H_4O_2$

Acetate as an example substrate:

- Anodic reaction: $CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^-$
- Cathodic reaction: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

Microbial Fuel Cells





Microbial Fuel Cells

Substrates used in microbial fuel cells

Acetate
Glucose
Corn Stover
Cellulose

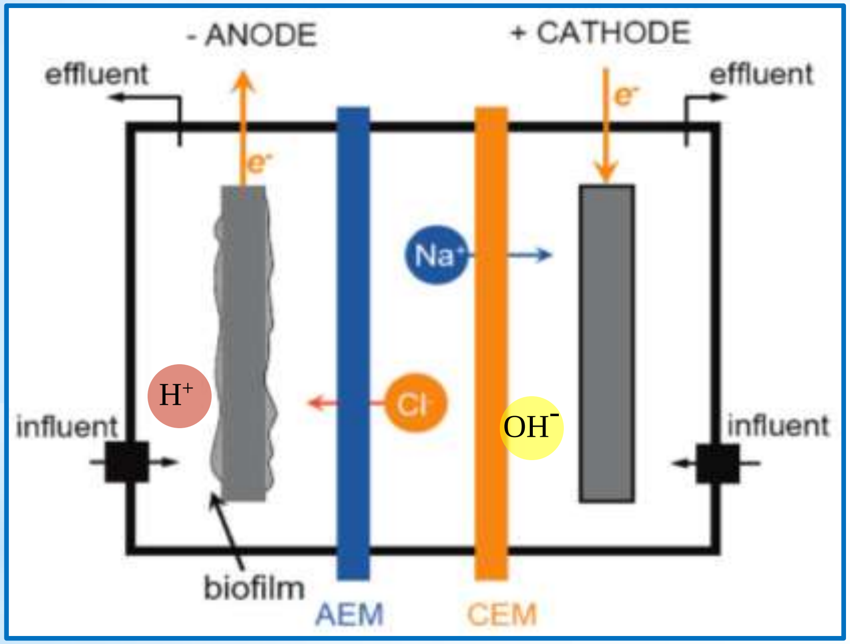
Municipal wastewater
Animal dairy wastewater
Food wastewater
Brewery wastewater
Landfill Leachate

Why Microbial Fuel Cells ?

Energy available in Substrates

- Based on the calorific content of glucose, an MFC can theoretically (at 100% efficiency during metabolism) deliver 3 kWh for every kilogram of organic matter (dry weight) in one single step.
- As a comparison, bio-methanization yields 1 kWh of electricity and 2 kWh of heat per kilogram of COD removed. This means that during substrate conversion in MFCs, hardly any energy is released in the form of external heat, and that all biochemical energy in the waste can be potentially converted into electricity.

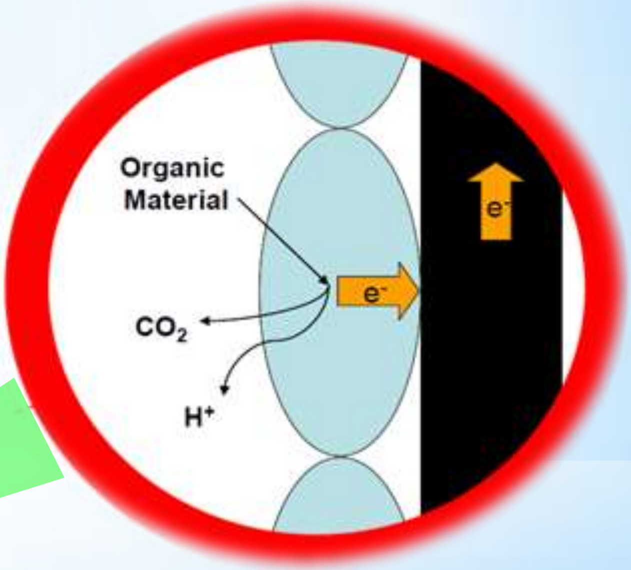
Microbial Desalination Cells

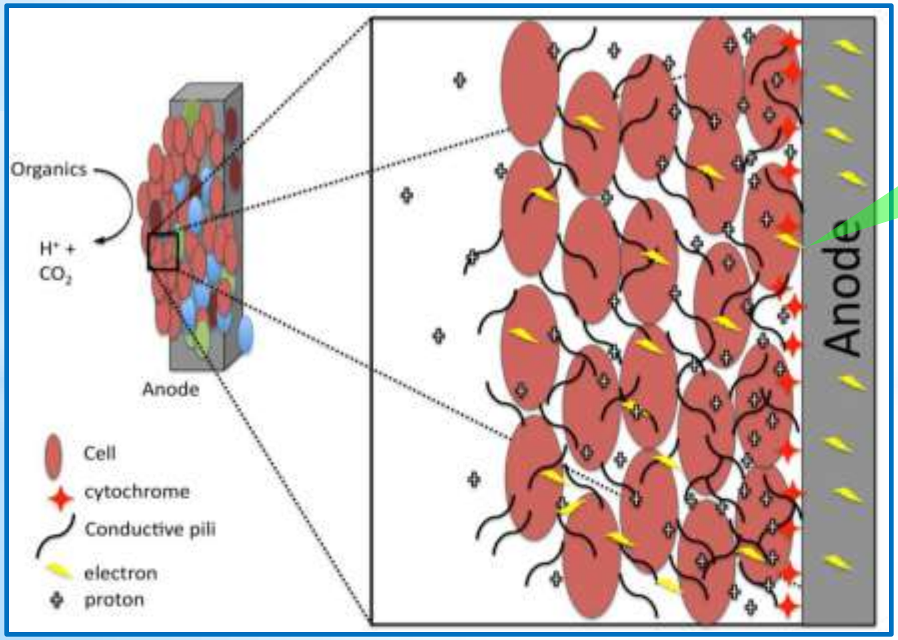


MDC: Inclusion of middle saline water chamber in MFC to allow ion migration

http://www.engr.psu.edu/ce/enve/logan/bioenergy/mfc_photos.htm

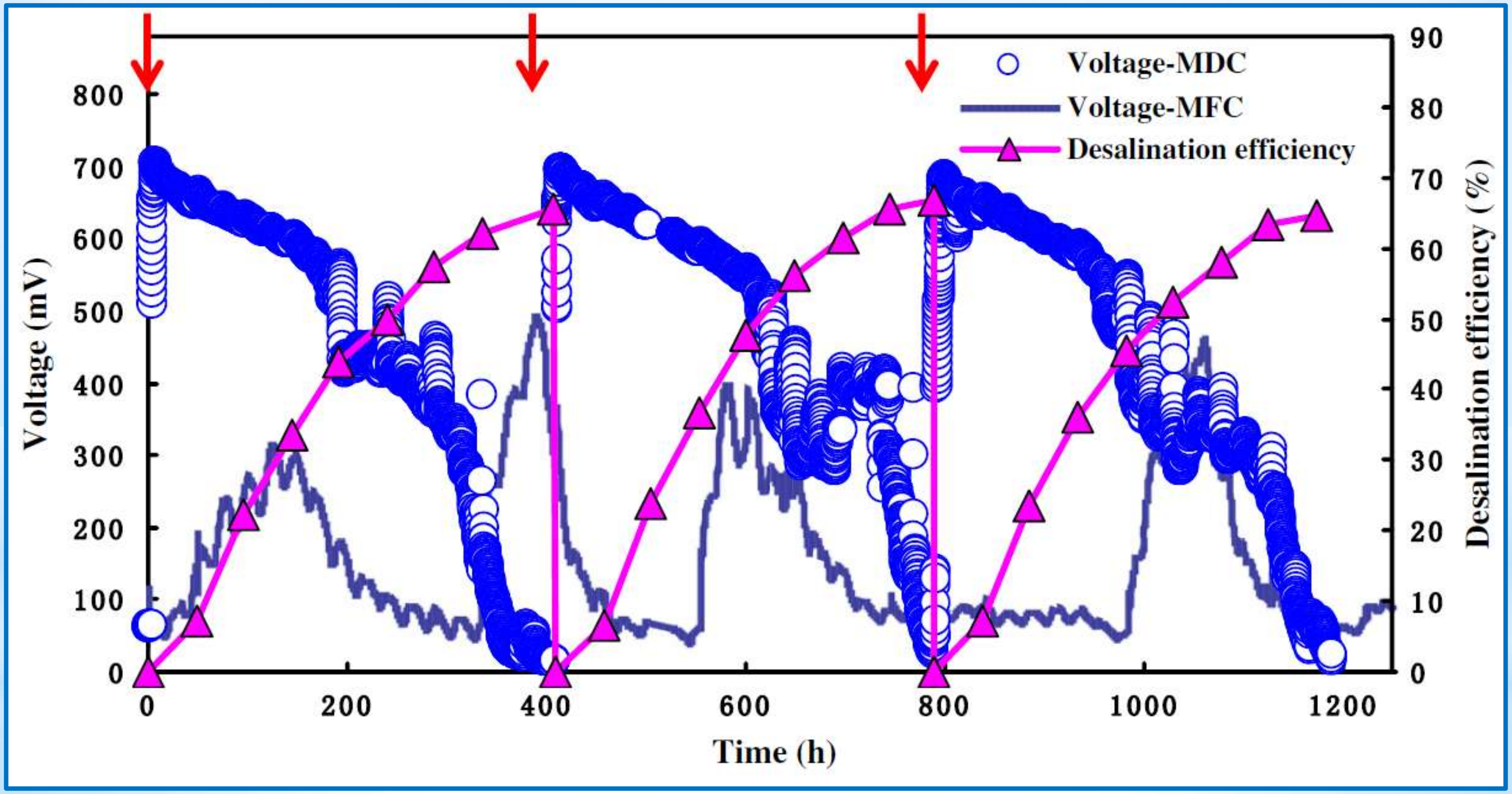
MDC: Electron Transfer





(Rozendal et al., 2008,
Franks & Nevin 2010)

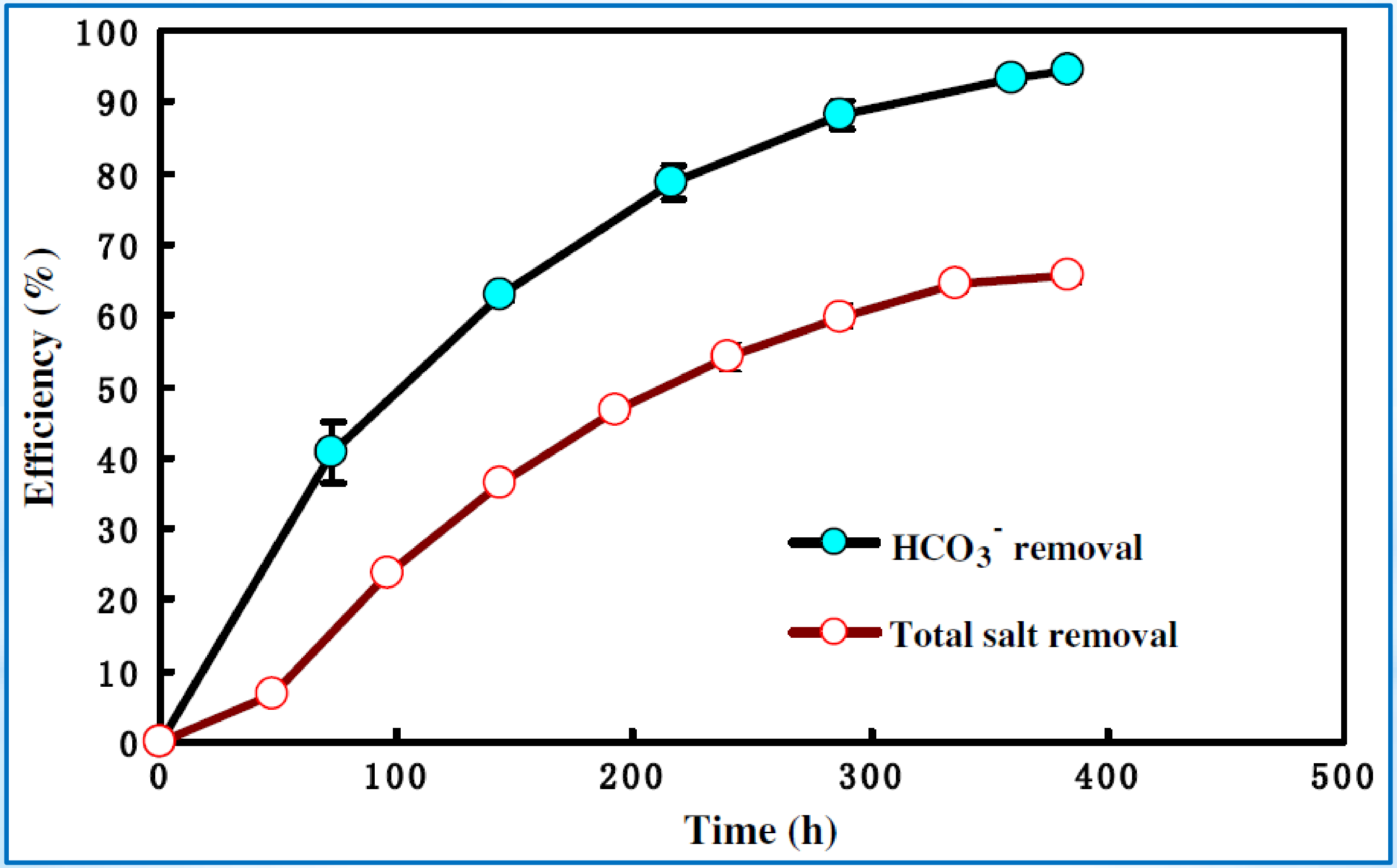
Microbial Desalination Cells



- MDC has higher electricity generation capability than MFC, well known technology

(Luo et al., 2012)

MDC: Salt and Hardness Removal

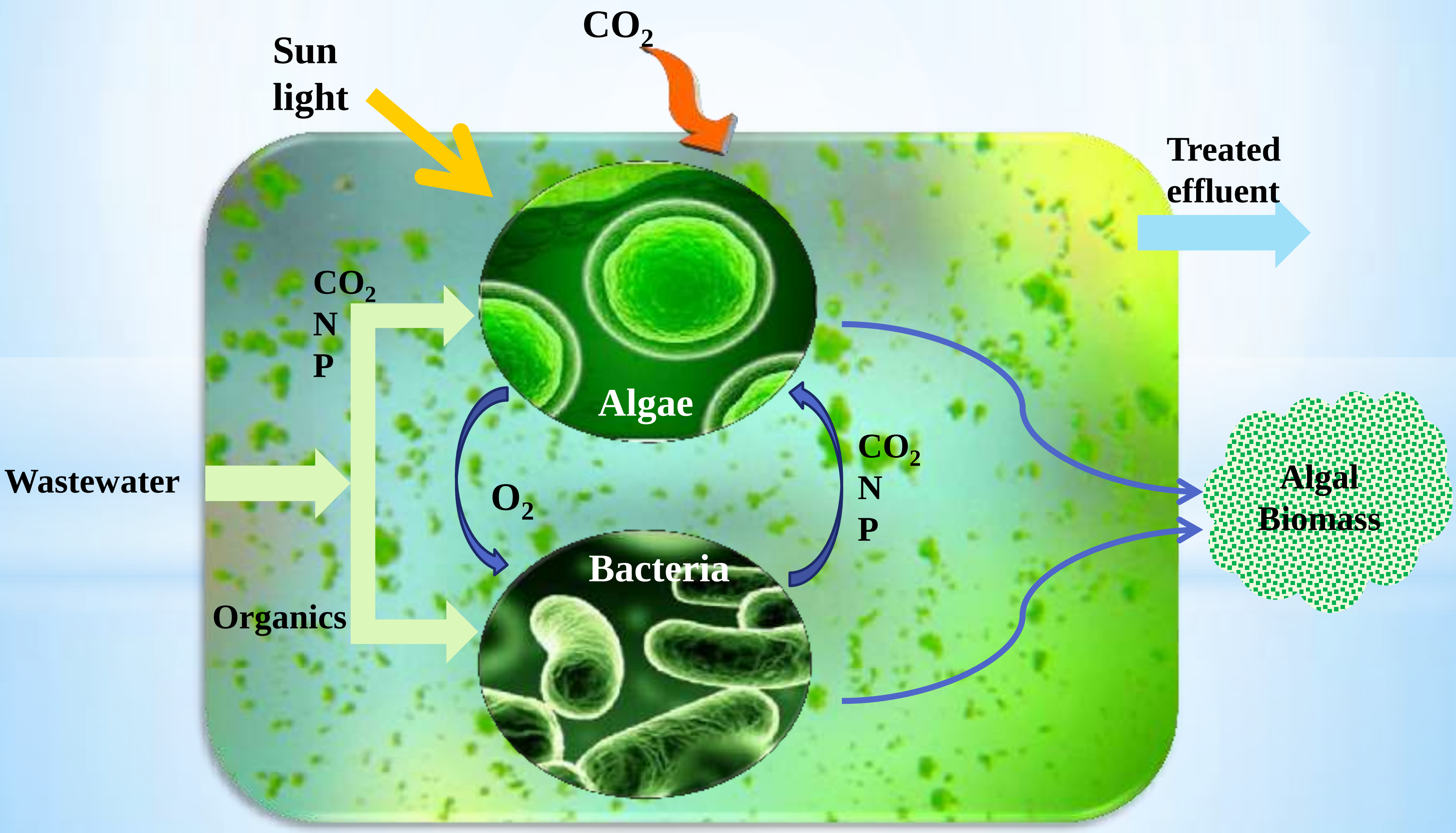


(Luo et al., 2012)

Microbial Desalination Cells

- About 90% of the salt can be removed
- **NO** need to pressurize the water or use an external power source
- Effective for desalinating water even at 35 g/L; compared to electrodialysis at salt concentrations up to 6 g/L

Algae Cultivation in Wastewater



Sun light

CO_2

Treated effluent

CO_2
N
P

Wastewater

Organics

Algae

O_2

CO_2
N
P

Bacteria

Algal Biomass

Water Foot Print & Nutrients

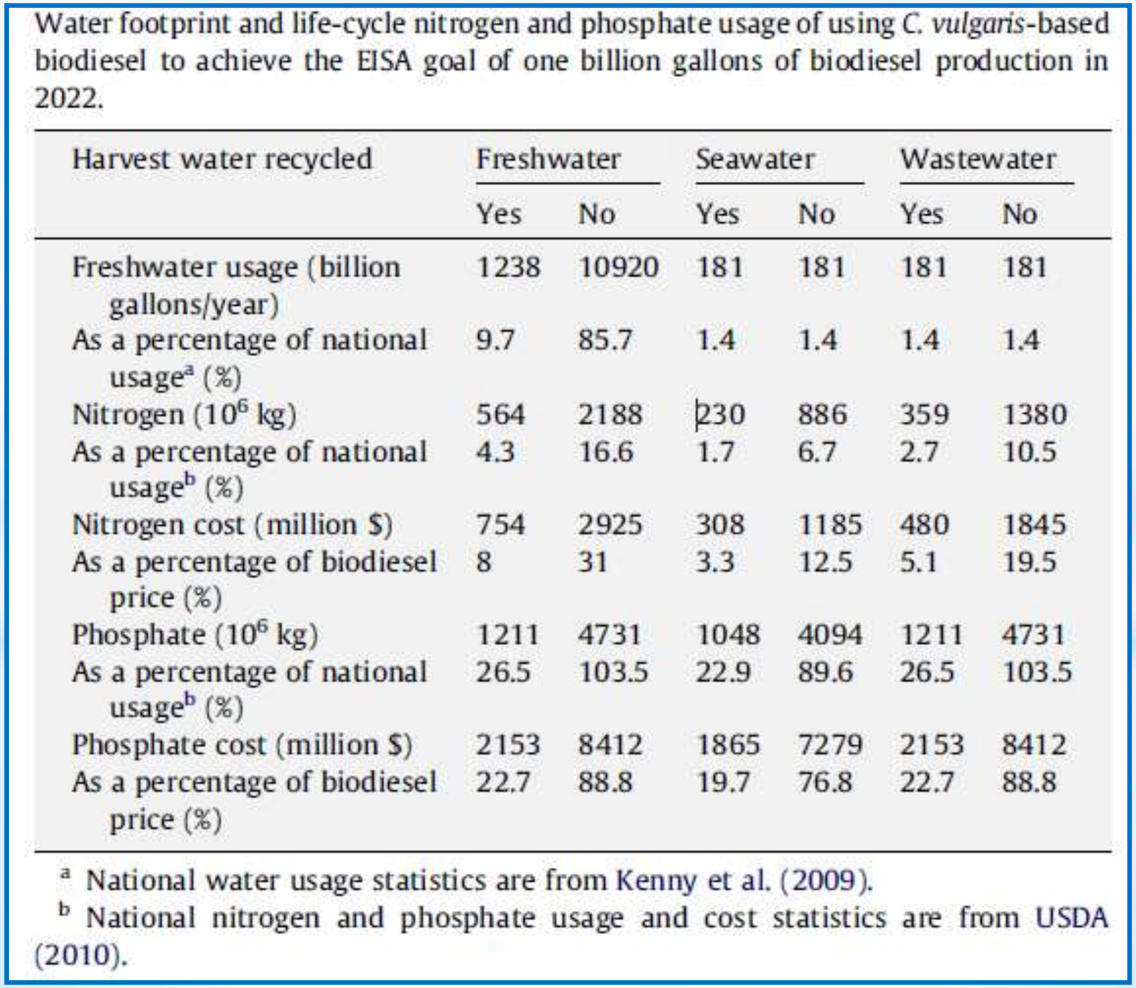
- 1 kg Microalgae biodiesel production requires
  - 3726 kg water
  - 0.33 kg nitrogen
  - 0.71 kg phosphate
- Recycling harvest water reduces
  - water usage by 84%
  - nutrients usage by 55%
- Using sea/wastewater as culture medium decreases 90% water requirement, and eliminates the need of all the nutrients except phosphate

Land Requirements for Biofuels

Dismukes et al., 2008

Water & Nutrients for Algal Biofuels

- Freshwater
- Seawater
- Wastewater



Water footprint and life-cycle nitrogen and phosphate usage of using *C. vulgaris*-based biodiesel to achieve the EISA goal of one billion gallons of biodiesel production in 2022.

Harvest water recycled	Freshwater		Seawater		Wastewater	
	Yes	No	Yes	No	Yes	No
Freshwater usage (billion gallons/year)	1238	10920	181	181	181	181
As a percentage of national usage[a] (%)	9.7	85.7	1.4	1.4	1.4	1.4
Nitrogen (10^6 kg)	564	2188	230	886	359	1380
As a percentage of national usage[b] (%)	4.3	16.6	1.7	6.7	2.7	10.5
Nitrogen cost (million $)	754	2925	308	1185	480	1845
As a percentage of biodiesel price (%)	8	31	3.3	12.5	5.1	19.5
Phosphate (10^6 kg)	1211	4731	1048	4094	1211	4731
As a percentage of national usage[b] (%)	26.5	103.5	22.9	89.6	26.5	103.5
Phosphate cost (million $)	2153	8412	1865	7279	2153	8412
As a percentage of biodiesel price (%)	22.7	88.8	19.7	76.8	22.7	88.8

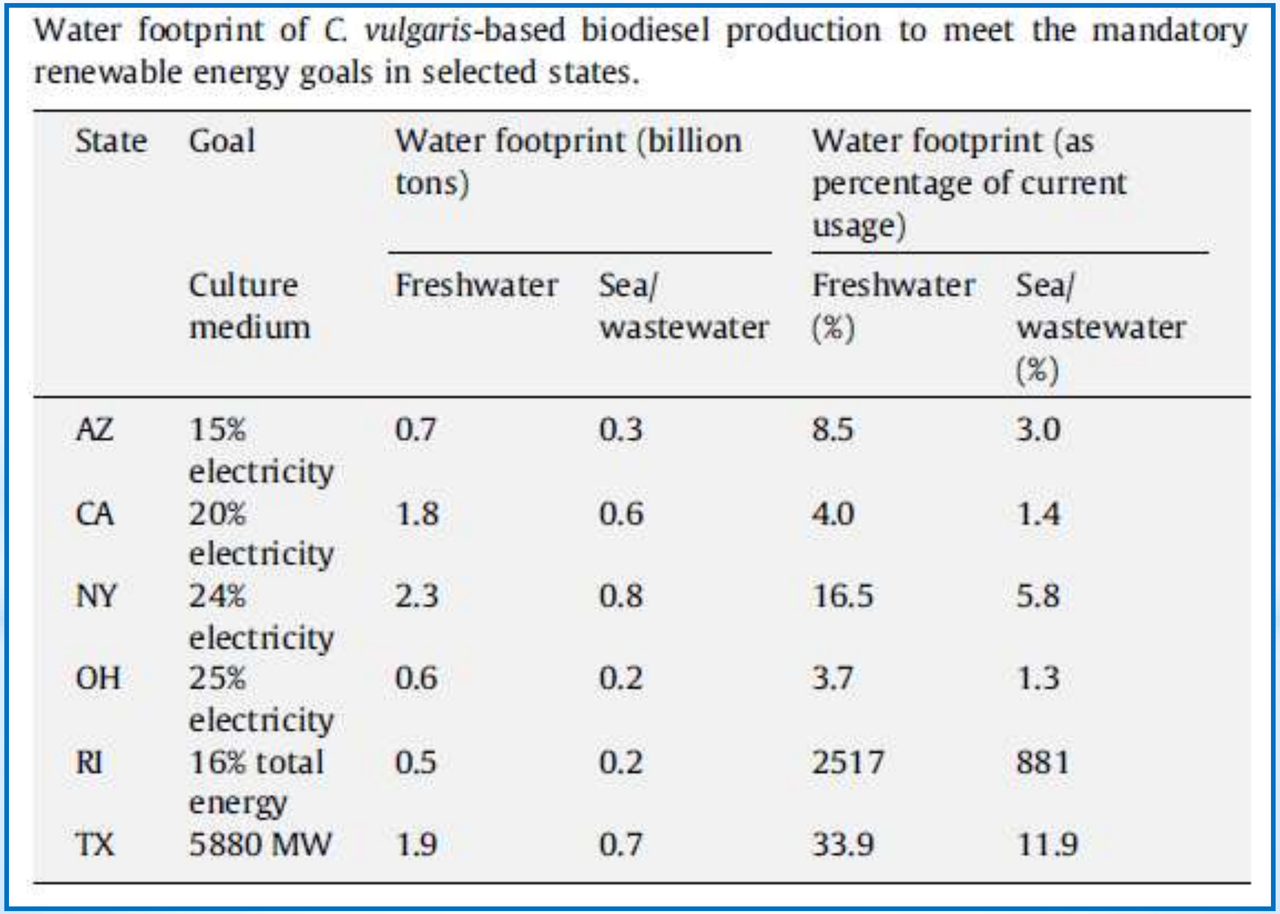
[a] National water usage statistics are from Kenny et al. (2009).

[b] National nitrogen and phosphate usage and cost statistics are from USDA (2010).

(Yang et al., 2011)

Water & Nutrients for Algal Biofuels

- Freshwater
- Seawater
- Wastewater



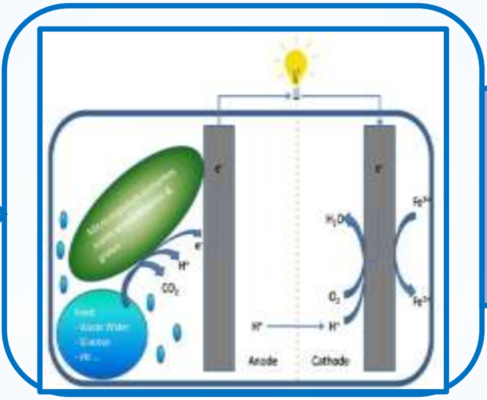
Water footprint of *C. vulgaris*-based biodiesel production to meet the mandatory renewable energy goals in selected states.

State	Goal	Water footprint (billion tons)		Water footprint (as percentage of current usage)	
	Culture medium	Freshwater	Sea/wastewater	Freshwater (%)	Sea/wastewater (%)
AZ	15% electricity	0.7	0.3	8.5	3.0
CA	20% electricity	1.8	0.6	4.0	1.4
NY	24% electricity	2.3	0.8	16.5	5.8
OH	25% electricity	0.6	0.2	3.7	1.3
RI	16% total energy	0.5	0.2	2517	881
TX	5880 MW	1.9	0.7	33.9	11.9

(Yang et al., 2011)

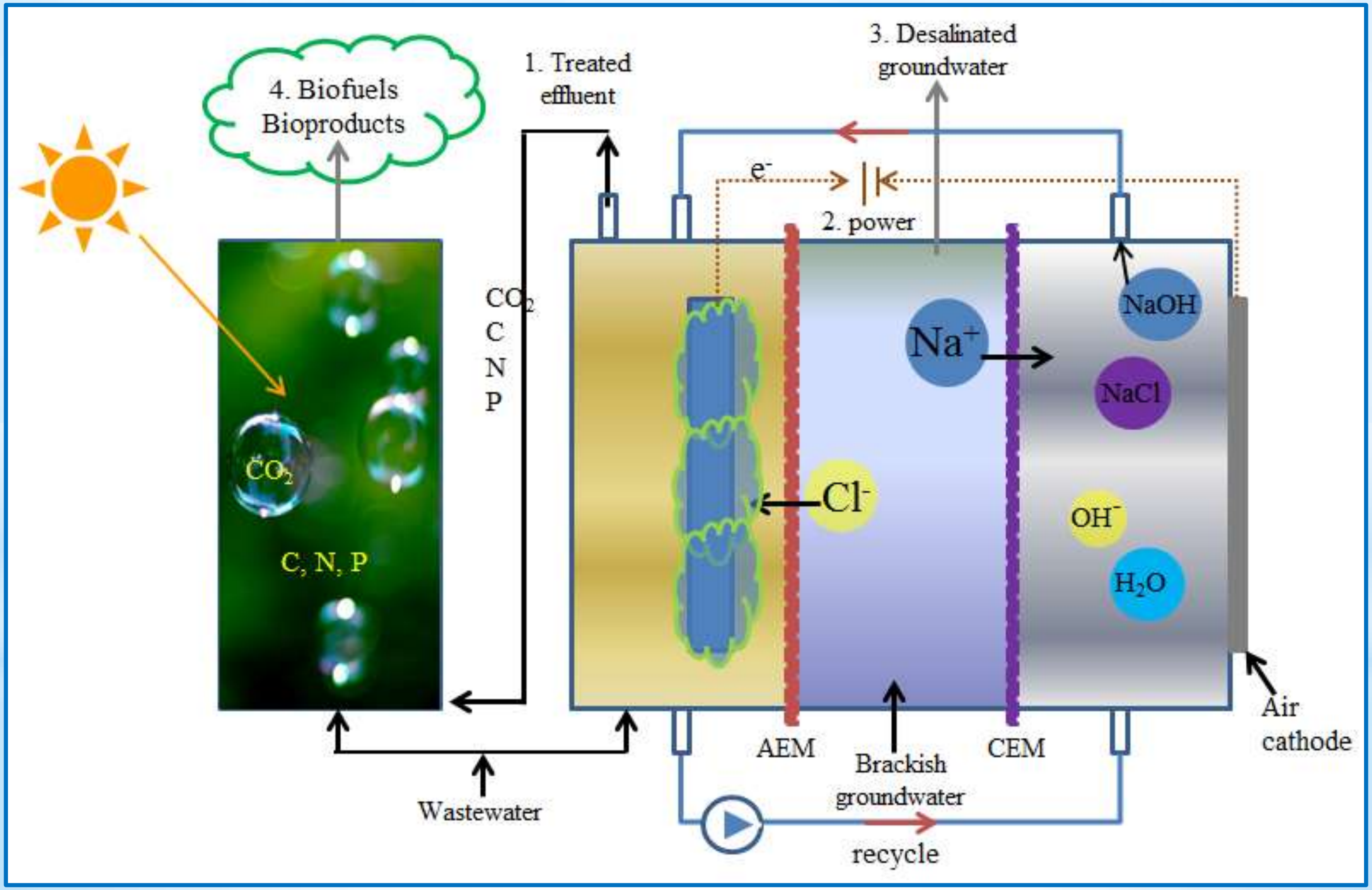
Integrated Algal-Microbial Desalination System

Wastewater &
Brackish water

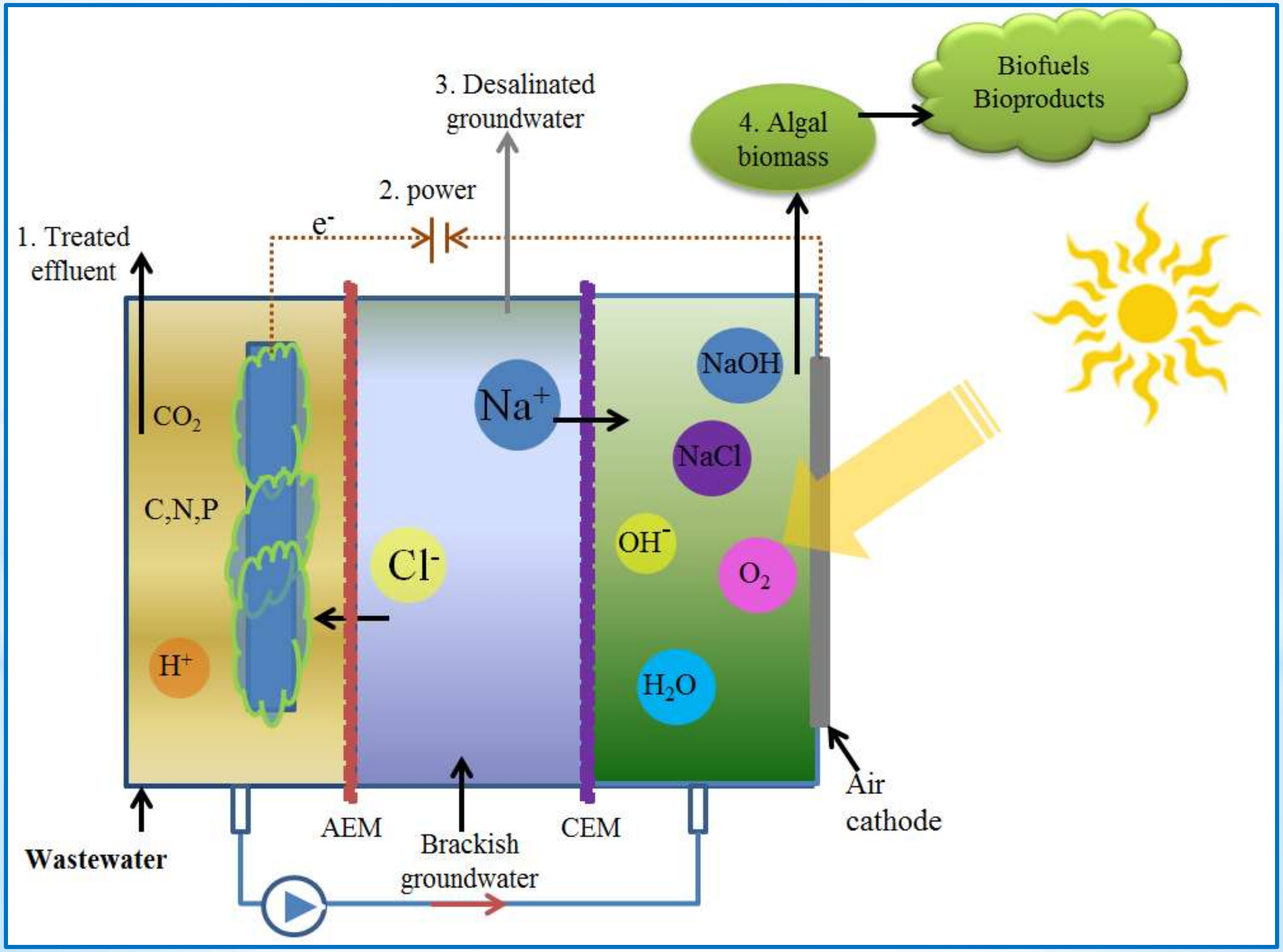


Power
Desalinated water
Algal biomass

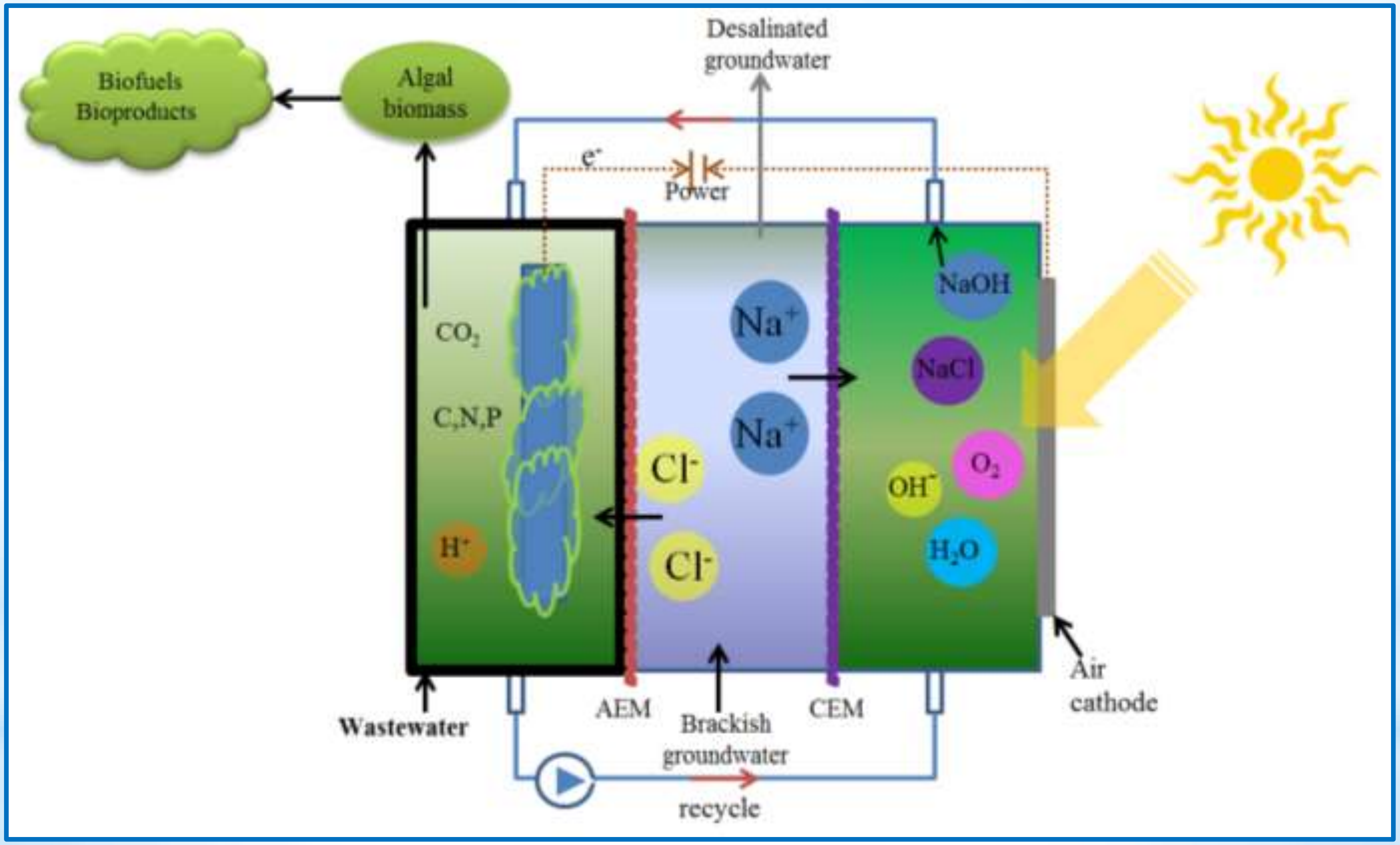
Integrated Algal-Microbial Desalination System



Algal-Microbial Desalination



Optimized Microbial Desalination

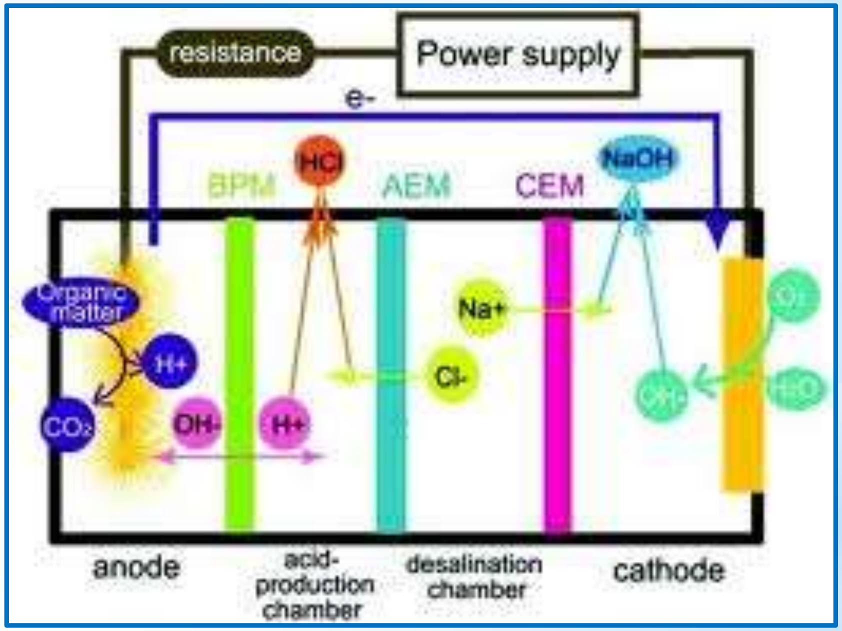


- Optimized algal growth
- Increased lipid production

Photosynthetic MDC

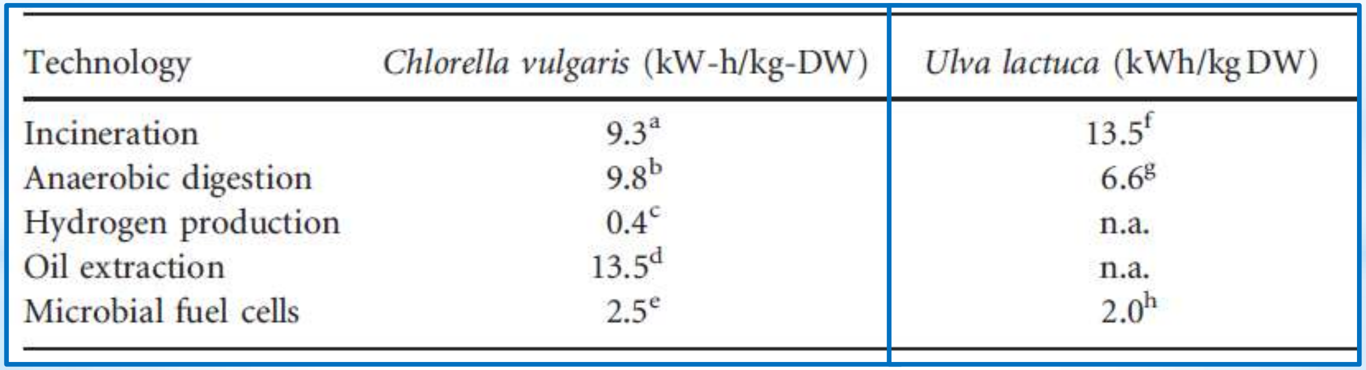
Highlights

- Self-sustainable
- CO_2 Extraction
- O_2 production/utilization
- Algal biomass production
- Water reuse and treatment
- Electricity production
- Biofuel production



Algal Biofuels

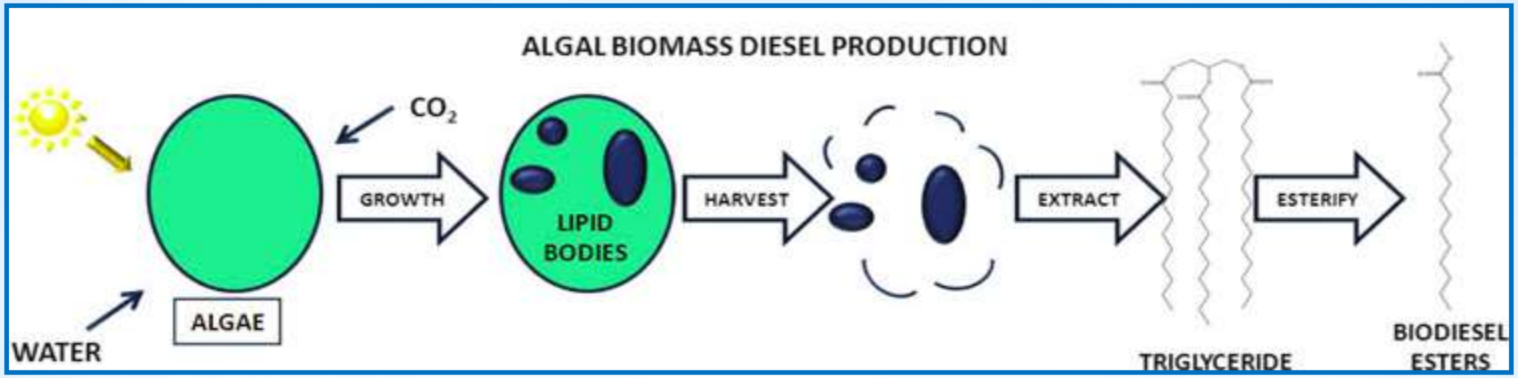
Bioelectricity ……Microbial Fuel Cells
Bio-hydrogen ……Microbial Fuel Cells
Bio-methane ……Anaerobic Digestion
Biodiesel ……Physical/Chemical Processes
Bio-syngas ……Incineration



Technology	*Chlorella vulgaris* (kW-h/kg-DW)	*Ulva lactuca* (kWh/kg DW)
Incineration	9.3[a]	13.5[f]
Anaerobic digestion	9.8[b]	6.6[g]
Hydrogen production	0.4[c]	n.a.
Oil extraction	13.5[d]	n.a.
Microbial fuel cells	2.5[e]	2.0[h]

(Velasquez-Orta et al., 2009, Sialve et al., 2009)

Energy from Algae



- Incineration of algal biomass into various fuels including production of methane and ethanol.
- The U.S. Department of Energy National Algal Biofuels Technology Roadmap estimates that the average gross energy content of algae biomass is 18 MJ/kg.
- Using this value, the maximum energy output is estimated to be 100.8 MJ/m^2-yr (5.6 kg/m^2-yr and 18 MJ/kg).

(U.S. DOE 2010)

Substrates Used in MFCs

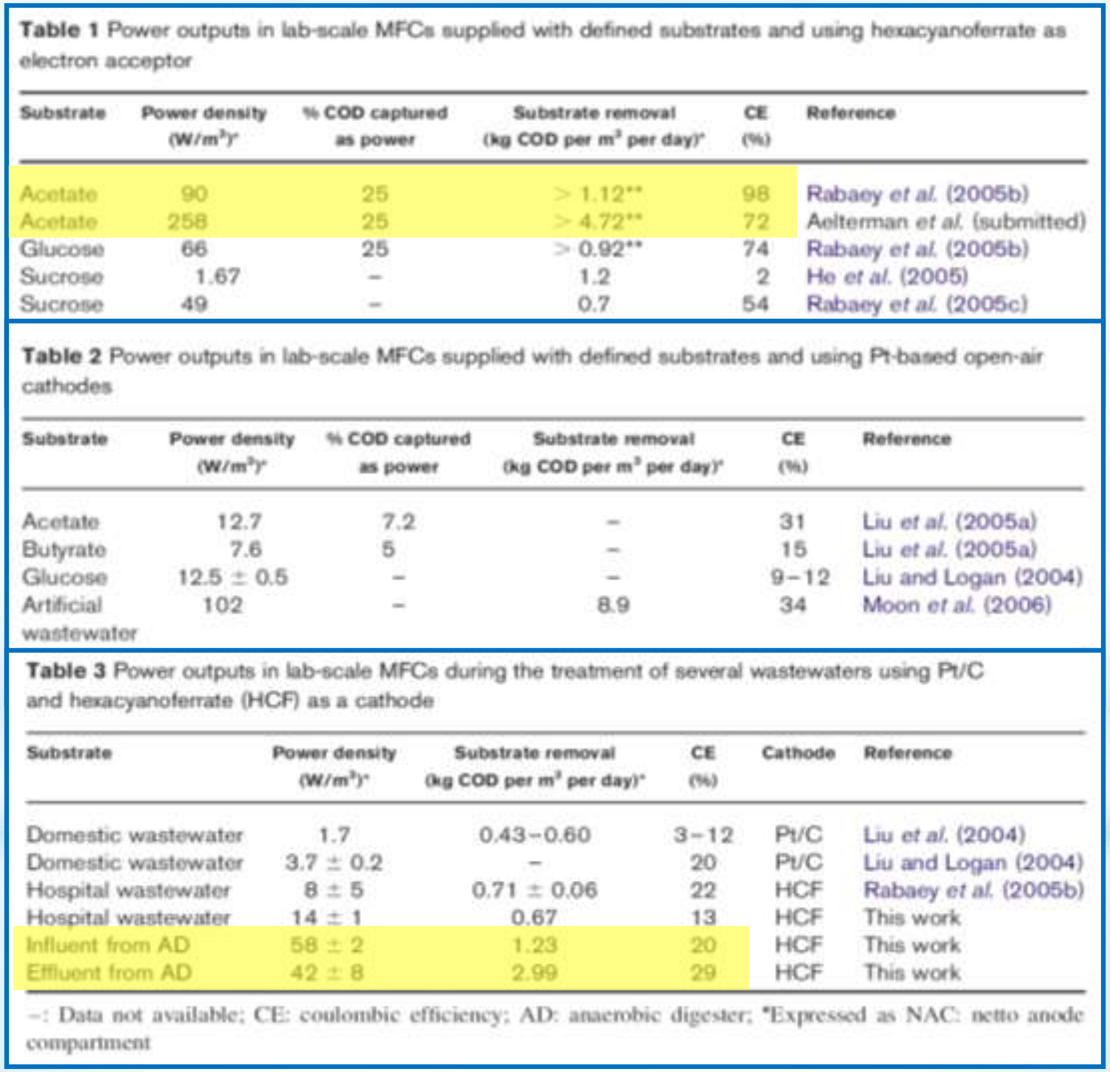


Table 1 Power outputs in lab-scale MFCs supplied with defined substrates and using hexacyanoferrate as electron acceptor

Substrate	Power density (W/m³)*	% COD captured as power	Substrate removal (kg COD per m³ per day)*	CE (%)	Reference
Acetate	90	25	> 1.12**	98	Rabaey *et al.* (2005b)
Acetate	258	25	> 4.72**	72	Aelterman *et al.* (submitted)
Glucose	66	25	> 0.92**	74	Rabaey *et al.* (2005b)
Sucrose	1.67	–	1.2	2	He *et al.* (2005)
Sucrose	49	–	0.7	54	Rabaey *et al.* (2005c)

Table 2 Power outputs in lab-scale MFCs supplied with defined substrates and using Pt-based open-air cathodes

Substrate	Power density (W/m³)*	% COD captured as power	Substrate removal (kg COD per m³ per day)*	CE (%)	Reference
Acetate	12.7	7.2	–	31	Liu *et al.* (2005a)
Butyrate	7.6	5	–	15	Liu *et al.* (2005a)
Glucose	12.5 ± 0.5	–	–	9–12	Liu and Logan (2004)
Artificial wastewater	102	–	8.9	34	Moon *et al.* (2006)

Table 3 Power outputs in lab-scale MFCs during the treatment of several wastewaters using Pt/C and hexacyanoferrate (HCF) as a cathode

Substrate	Power density (W/m³)*	Substrate removal (kg COD per m³ per day)*	CE (%)	Cathode	Reference
Domestic wastewater	1.7	0.43–0.60	3–12	Pt/C	Liu *et al.* (2004)
Domestic wastewater	3.7 ± 0.2	–	20	Pt/C	Liu and Logan (2004)
Hospital wastewater	8 ± 5	0.71 ± 0.06	22	HCF	Rabaey *et al.* (2005b)
Hospital wastewater	14 ± 1	0.67	13	HCF	This work
Influent from AD	58 ± 2	1.23	20	HCF	This work
Effluent from AD	42 ± 8	2.99	29	HCF	This work

–: Data not available; CE: coulombic efficiency; AD: anaerobic digester; *Expressed as NAC: netto anode compartment

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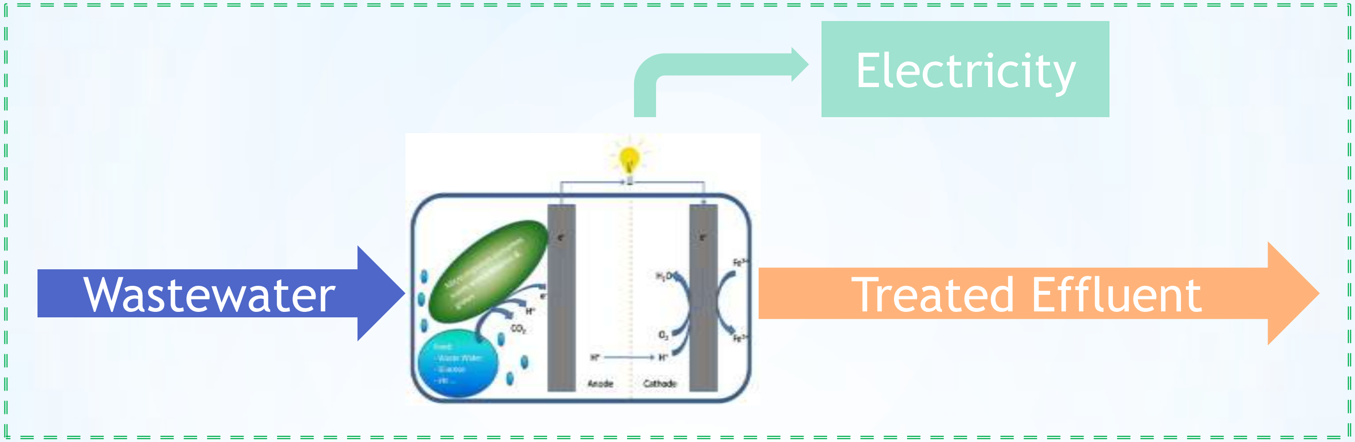
(Rabaey et al., 2006)

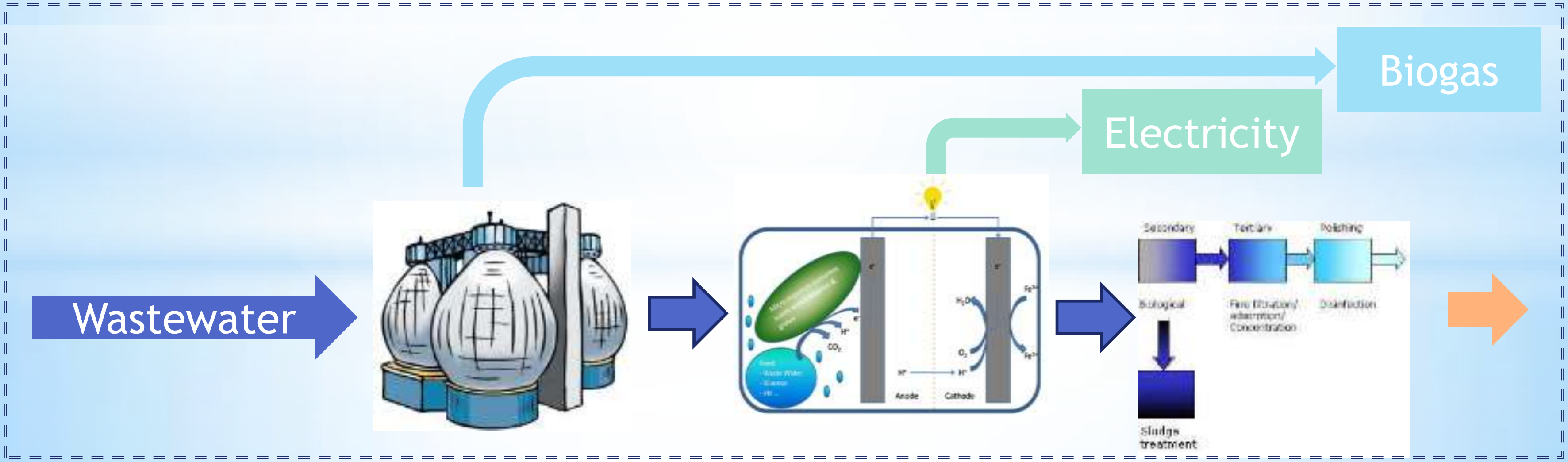
MDC for Wastewater Treatment



Electricity

Wastewater

Treated Effluent



Biogas

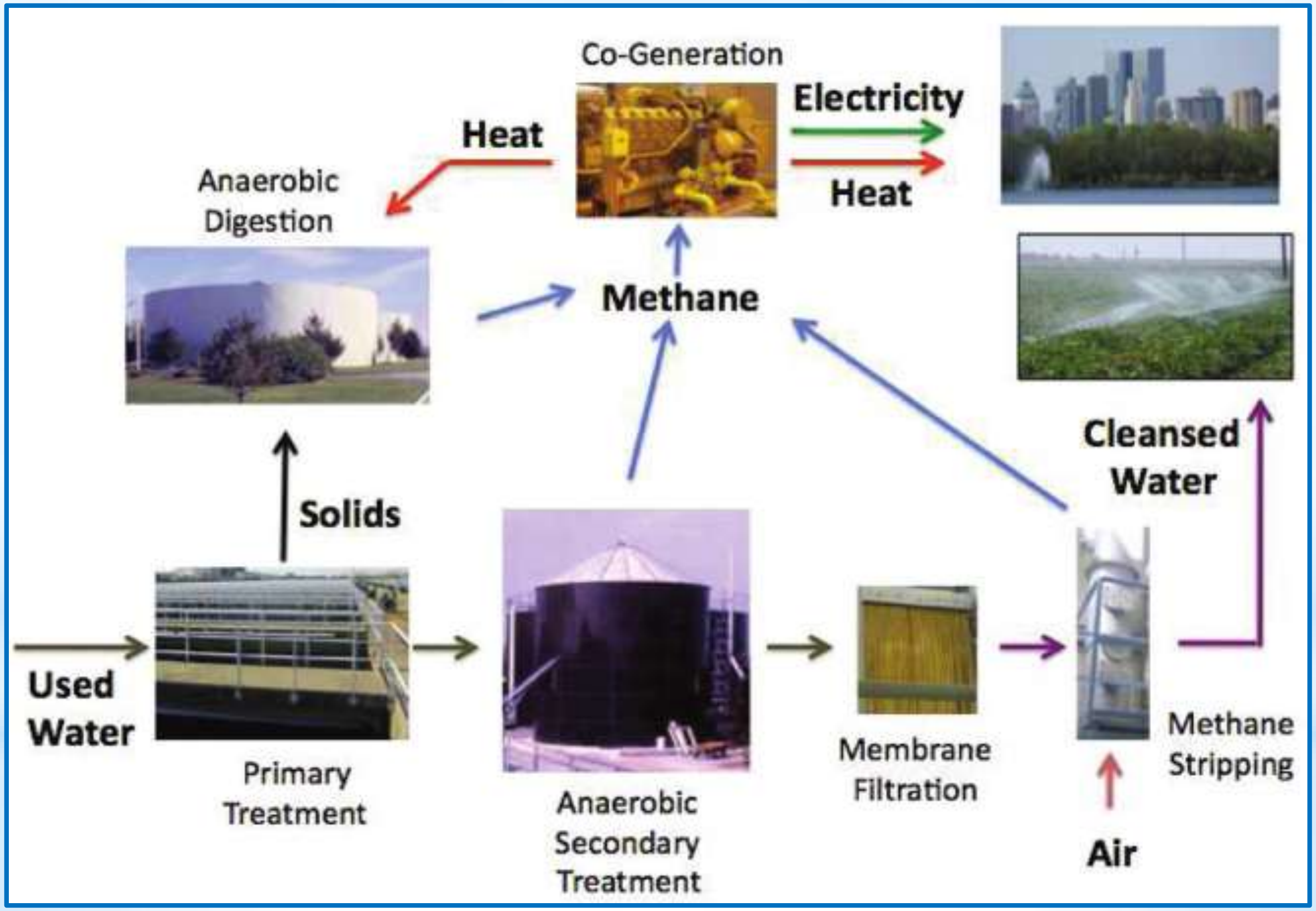
Electricity

Wastewater

(Rabaey et al., 2006)

Wastewater Treatment: Energy Routes

Anaerobic treatment and digestion



(Mc Carty et al., 2011)

MDC Challenges

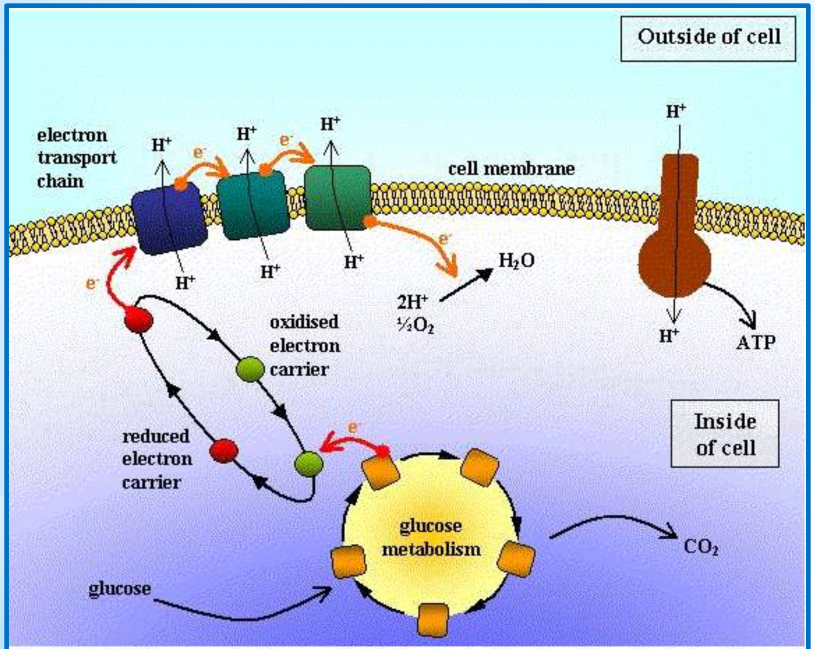
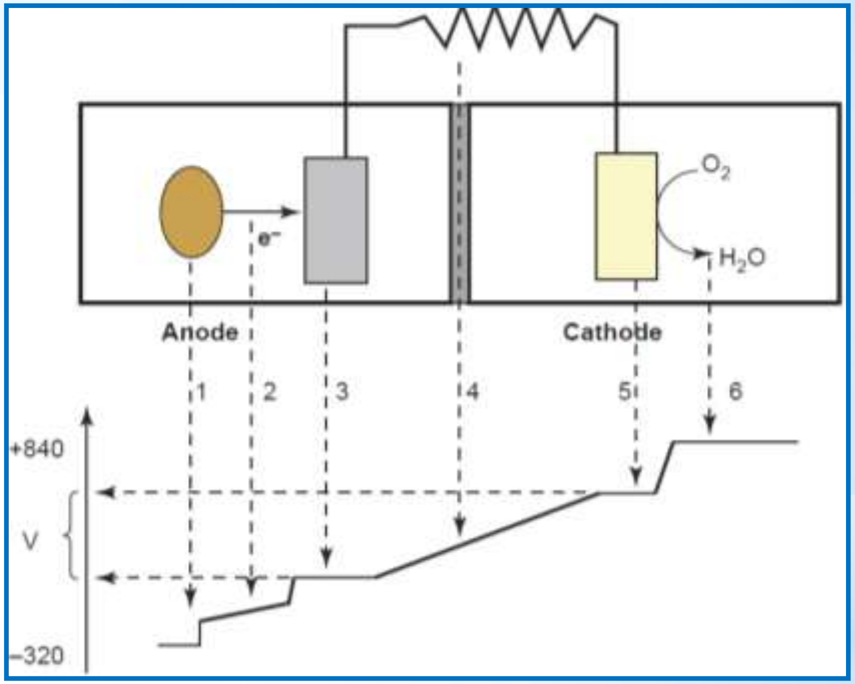
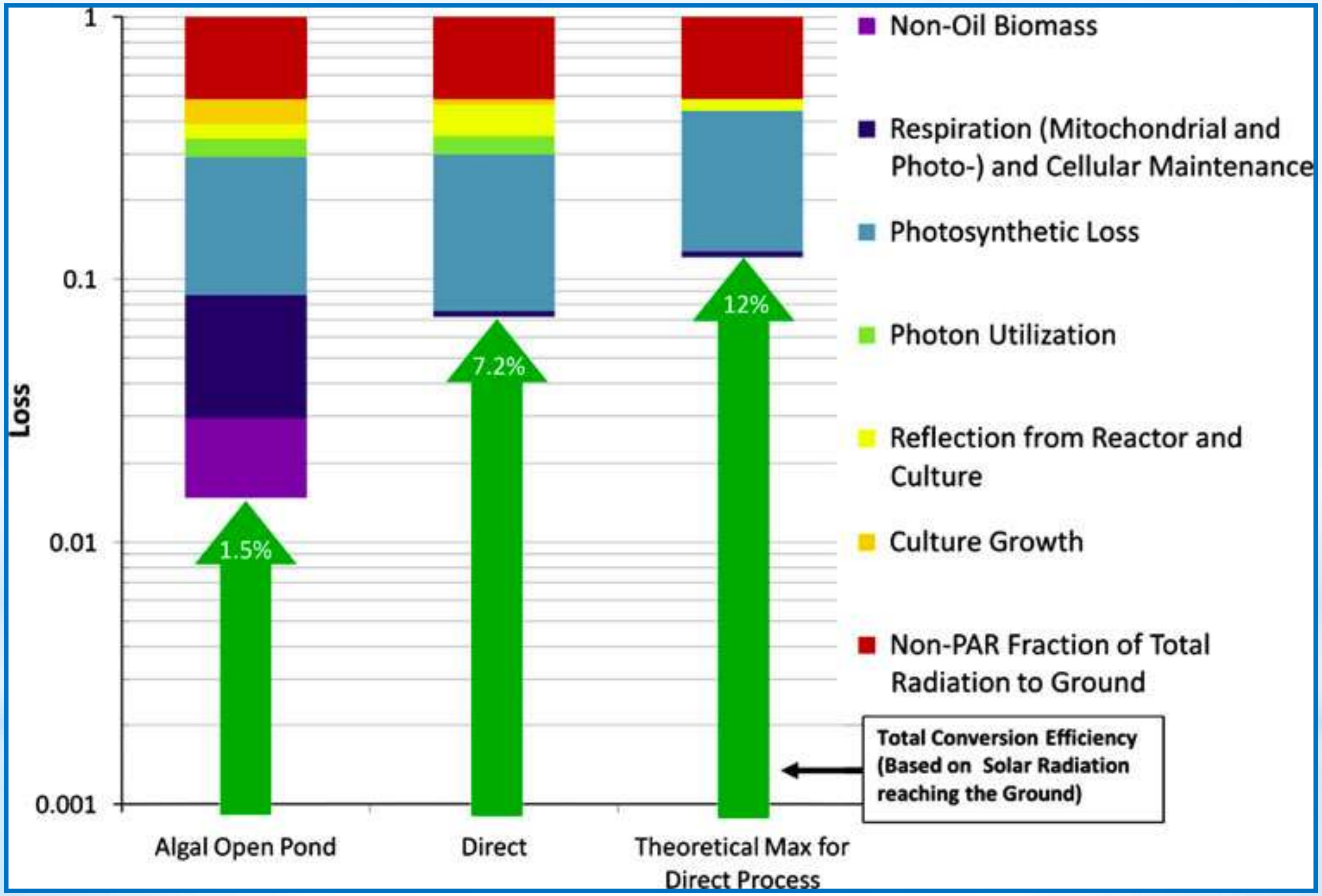


Figure 1. Glucose metabolism and the ET transport chain of bacteria and mitochondria



Potential losses during electron transfer in a MFC. 1. Loss owing to bacterial electron transfer. 2. Losses owing to electrolyte resistance. 3 Losses at the anode. 4. Losses at the MFC resistance (useful potential difference) and membrane resistance losses. 5. Losses at the cathode. 6: Losses owing to electron acceptor reduction. (Rabaey and Verstrate 2005, Schroder 2007)

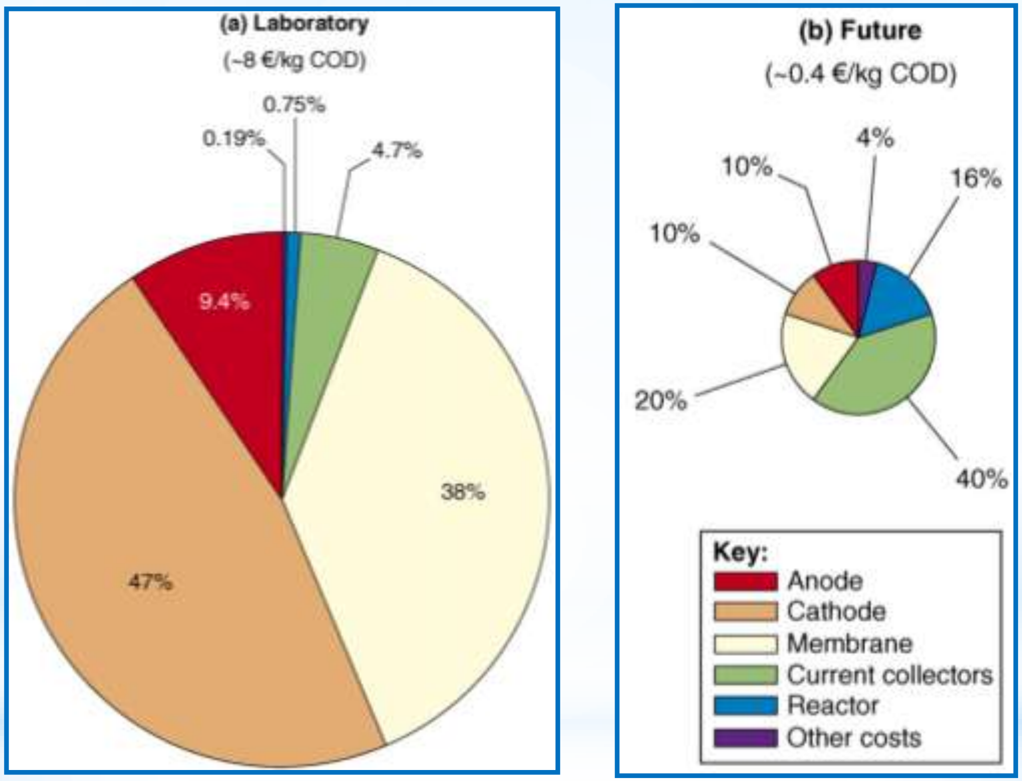
Algal Growth Challenges



Algal Growth Challenges

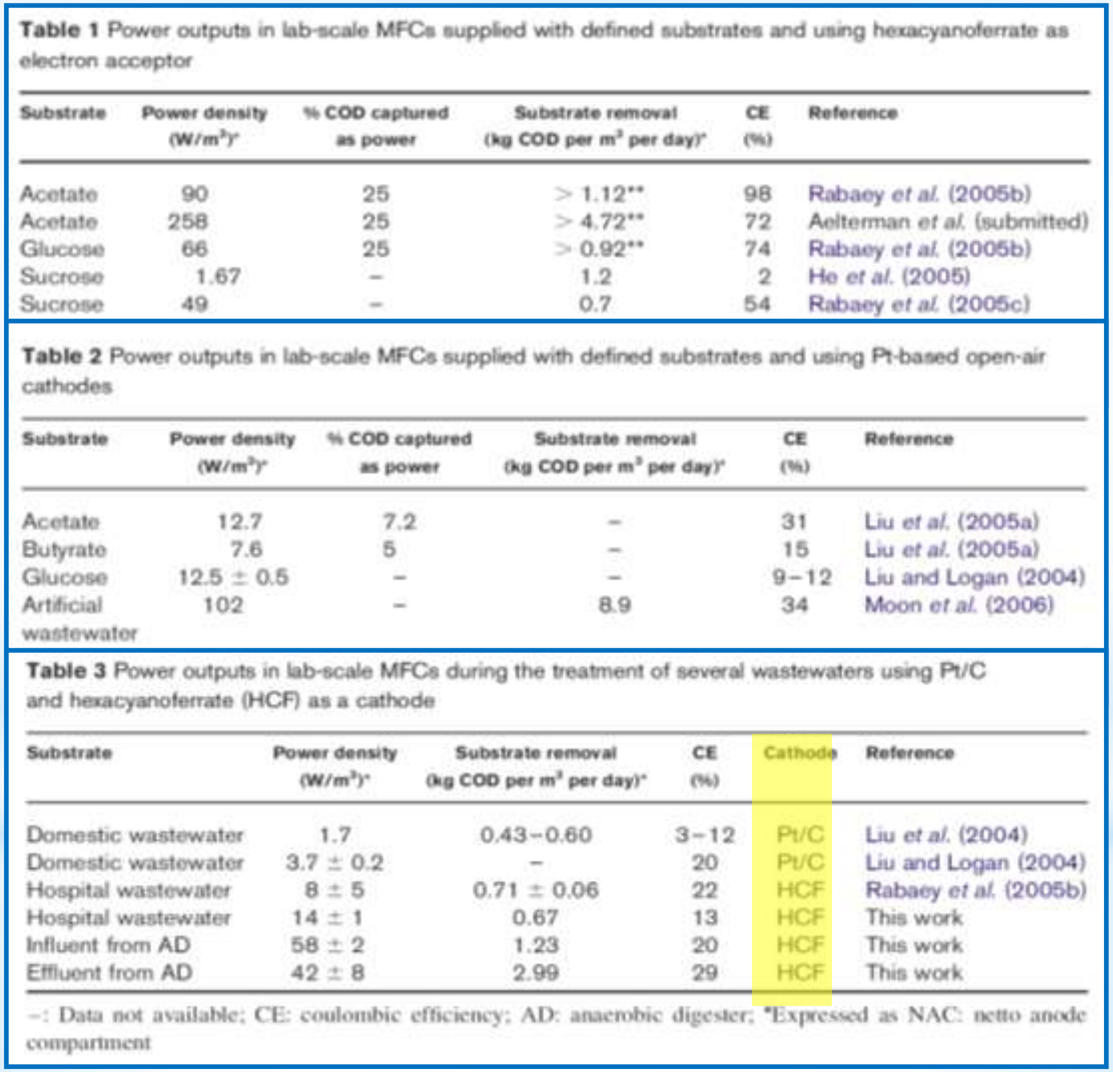
- The production costs of algae cultivation must be decreased drastically, to one-tenth of the current level ($20-50/gal).
- Increasing the photosynthetic efficiency is one of the most important stipulations.
- Improved reactor designs and use more efficient algae.
- Saving nutrients by making use of waste and residual flows and recycling of these nutrients.
- Furthermore, use of energy-efficient pumps and better harvest and downstream processing methods (bio-refining) can significantly contribute to reduce costs, but also to improve the final product.

Future Feasibility



(Pant et al., 2007,
Rozendal et al., 2008)

Materials used in MFCs



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Economics

System	Product	Capital costs ($/kg COD)	Product revenue ($/kg COD)	Offset (revenue - costs) ($/kg COD)
Acitvated sludge	N/A	0.125	-0.375	-0.5
Anaerobic Digestion	CH_4	0.0125	0.125	0.125
MFC	Electricity (10)	0.5	0.25	-0.25
MEC	H_2 (10)	0.5	0.75	0.25

Item	Material	Present (laboratory) $	Future substitutes ($)
Anode	graphite (per m^2)	125	6.25
Cathode	platinum (per m^2)	625	6.25
Membrane	(per m^2)	500	12.5
Current collectors	(per m^2)	31.25	12.5
Reactors	(per m^3)	5000	5000
Others		1250	1250

(Rozendal et al., 2008)

Thank You
&
Questions