New energy conversions using microorganisms and electrodes

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Wastewater contains energy!
From aerobic to anaerobic wastewater treatment

Before 1970/80’s

COD = chemical oxygen demand = measure for organic components in wastewater

Source: http://www.uasb.org
A next generation wastewater treatment is required

Biogas Production

Biogas Treatment (a.o. $\text{H}_2\text{S}$ removal)

Electricity Production (gasmotor)

Efficiency: +/- 30%

# of Units: At least 3

Source: http://www.paques.nl
Electrochemically active microorganisms
Microorganisms catalyze the oxidation of wastewater (acetate) at the bio-anode

\[
\text{CH}_3\text{COOH} + 2 \text{H}_2\text{O} \rightarrow 2 \text{CO}_2 + 8 \text{H}^+ + 8 \text{e}^- 
\]
Microbial Fuel Cells convert wastewater directly into electricity.
Cell configurations for bioelectrochemical systems
Versatility in reactions and applications

Electrode potential (V vs NHE)

- $\text{H}_2\text{O}/\text{O}_2$ (4e⁻) 0.81V
- $\text{O}_2/\text{H}_2\text{O}$ (4e⁻) 0.81V
- $\text{NO}_3^-/\text{N}_2$ (5e⁻) 0.73V
- $\text{Cu}^{2+}/\text{Cu}$ (2e⁻) 0.29V
- $\text{H}^+/\text{H}_2$ (2e⁻) -0.41V
- Acetate/$\text{HCO}_3^-$ (8e⁻) -0.29V

MFC
MEC

Glucose/$\text{HCO}_3^-$ (24e⁻) -0.43V

Wageningen University
Microbial Electrolysis Cells for hydrogen production from wastewater
We need a breakthrough…
... and we need experience with scaling-up

- Decreasing internal resistance
- Decreasing material cost
- Increasing revenues (niche applications)
Capacitive electrodes for bio-anodes
Improved performance with a capacitive layer

Deeke et al., 2012, ES&T
Activated carbon granules as a basis for a fluidized bed Microbial Fuel Cell

Capacitive granules (activated carbon) 500 m²/g

Acetate  CO₂ + H⁺

Electro-active biofilm
Capacitive Fluidized Bio-anode

Charging reactor

N₂ gas

Waste water

Clean water

Discharge cell

O₂ + H⁺

H₂O

Cathode

Anode
Increase in current density with increasing granule loading: proof of principle

Deeke et al., 2015, ES&T
Measure single granule behaviour under controlled conditions

1.5 cm
One single granule can produce 0.6 mA: >1,000x more than achieved in reactor
Understand fundamentals: Capacitance of electrode influenced by biofilm

![Graph showing capacitance comparison between biotic and abiotic conditions for GAC, PK, and GG samples.](image-url)

- **GAC** and **PK** samples exhibit higher capacitance in a capacitive environment compared to a non-capacitive environment.
- **GG** shows negligible capacitance in both environments.

The graph indicates that the capacitance of the electrode is significantly influenced by the presence of a biofilm, with biotic conditions generally leading to higher capacitance values.
Develop a reactor that can achieve higher conversion rates (current)
Nitrogen and energy recovery from urine: high soluble COD and NH$_4^+$ concentrations
Value from Urine principle

Collection

Struvite recovery

BES

NH\textsubscript{3} recovery
Microorganisms catalyze N and energy recovery from urine
Acclimation of bio-anodes to urine
Piloting urine treatment (30 persons) at Wetterskip Fryslan & Wetsus
Proof of principle: copper and electricity recovery

Ter Heijne et al. ES&T, 2012
Cell configuration with low internal resistance
High-rate microbial fuel cell with copper
Plant Microbial Fuel Cell

- New source
- 24 h/d
- Self repairing
- No fine dust emissions
Proof-of-principle: plants produce electricity

Figure 2. Plant-MFC proof of principle. Cell voltage (mV) of two plant-MFCs and two blank MFCs.
Plant-e
living plants generate electricity
Power to (bio-\textsuperscript{\textregistered})gas
Biocathodes offer an energy efficient alternative for power to gas
Continuous and stable methane production

<table>
<thead>
<tr>
<th>Phase</th>
<th>Methane production rate (m³/m³ per day)</th>
<th>( \eta_{\text{Coulombic}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>0.2119</td>
<td>59.49</td>
</tr>
<tr>
<td>Phase II</td>
<td>0.2875</td>
<td>56.23</td>
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<tr>
<td>Phase III</td>
<td>0.2454</td>
<td>58.31</td>
</tr>
<tr>
<td>Phase IV</td>
<td>0.2604</td>
<td>55.35</td>
</tr>
</tbody>
</table>
Electricity storage as chemical energy

Electrode potential (V vs NHE)

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- $\text{NO}_3^−/\text{N}_2$ (5e$^-$) 0.73V
- $\text{Cu}^{2+}/\text{Cu}$ (2e$^-$) 0.29V
- Acetate/$\text{HCO}_3^−$ (8e$^-$) -0.29V
- $\text{HCO}_3^−$/methane (8e$^-$) -0.25V
- $\text{HCO}_3^−$/acetate (8e$^-$) -0.29V
- $\text{HCO}_3^−$/ethanol (12e$^-$) -0.31V
- acetate/ethanol (4e$^-$) -0.39V
- $\text{H}^+$/H$_2$ (2e$^-$) -0.41V

Oxidation and reduction
Acetate production at biocathodes as alternative to methane

Biobattery for storage of electricity in the form of acetate: proof of principle

\[
\text{Ac}^- + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2 + \text{H}^+ + \text{Ac}^-\]
Biobattery perspective depends on maximum acetate concentration.
Microorganisms and electrodes offer new exciting possibilities for energy conversions

- Capacitive granules
- Urine treatment
- Copper recovery
- Plant MFC
- Biobattery
Thank you for your attention

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