Current Trends in Anaerobic Digestion

Diversifying from waste(water) treatment to re-source oriented energetic conversion techniques

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AD ↔ Energy: heat, energy carriers, electricity

COD → Anaerobic conversions

Energy content biomass: ≈ 13.5 MJ/kg COD

“Conservation of electrons”

“heat”

Reduced gases: CH$_4$, H$_2$, (H$_2$S)

Electrons: MFC/BES

Reduced liquid compounds: VFA, alcohols, LCFA, alkanes??*

*Zengler et al., ’99, Nature 401, 266-269: alkanes→CH$_4$
AD ↔ Energy: heat, energy carriers, electricity

“heat”

Reduced gases: CH$_4$, H$_2$, (H$_2$S)

COD

Anaerobic conversions

Energy content biomass:
≈ 13.5 MJ/kg COD

Sludge

“Conservation of electrons”

SUBSTRATES:
- Solid wastes
- Slurries
- Manure
- Energy crops
- Co-digestion
- Wastewater
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Energy recovery in anaerobic wastewater treatment

Completely mixed

(Bio)gas

influent  effluent

Physical retention

Relative capacity: 1

Immobilised biomass

Relative capacity: 5

Enhanced contact

Relative capacity: 75

Development of “high-rate” anaerobic treatment systems
1. Sludge/biomass inlet
2. Gas baffle plates
3. Return settled sludge

1. Sludge/water mixture
2. Settled sludge
Application of Multi-layer settling system

From UASB....

..to IC (EGSB)
Historically applied anaerobic processes

(1981 – 2007 (Jan.) N= 2266)

UASB 50%

IC 15%

EGSB 12%

AF 6%

CSTR 7%

LAG 4%

HYBR 3%

FB 2%

* 1%

(Granular) sludge bed based: 77%

* References with incomplete data (1%)

Source: Worldref. 04-2007

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Currently Applied Anaerobic Processes

(2002 – 2007 (Jan.), N= 610)

Expanded Bed Reactors: 55%  
EGSB 22%  
UASB 34%

(Granular) sludge bed based: 89%

* References with incomplete data (1%)
Source: Worldref. 04-2007
Full Scale Expanded Bed versus UASB Systems

Percentage of yearly projects

Year


UASB

Expanded Bed (EGSB, IC, FB)
Full scale AWWT at beer brewery

UASB
Bavaria, Lieshout

IC
Heineken, Den Bosch
Worldwide cumulative anaerobic references

Anaerobic Industrial Wastewater Reactors, census 2007
over 2200 registered high-rate reactors
+ \approx 500 (?) non registered ("home made")

Van Lier, Wat.Sci.Technol. 57(8), 2008; Data collected by Yolanda Yspeert
### High-rate Anaerobic Applications in Industries

Number of installed reactors, \(N=2266\) (Jan. 2007)

<table>
<thead>
<tr>
<th>AGRO-FOOD INDUSTRY</th>
<th>BEVERAGE</th>
<th>ALCOHOL DISTILLERY</th>
<th>PULP &amp; PAPER</th>
<th>MISCELLANEOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(36%)</td>
<td>(29%)</td>
<td>(10%)</td>
<td>(11%)</td>
<td>(14%)</td>
</tr>
<tr>
<td>Sugar</td>
<td>Beer</td>
<td>Sugar cane juice</td>
<td>Recycle paper</td>
<td>Chemical</td>
</tr>
<tr>
<td>Potato</td>
<td>Malting</td>
<td>Sugar cane molasses</td>
<td>Mechanical pulp</td>
<td>Pharmaceutical</td>
</tr>
<tr>
<td>Starch</td>
<td>Soft drink</td>
<td>Sugar beet molasses</td>
<td>NSSC</td>
<td>Sludge liquor</td>
</tr>
<tr>
<td>Yeast</td>
<td>Fruit juice</td>
<td>Grape wine</td>
<td>Sulphite pulp</td>
<td>Municipal sewage</td>
</tr>
<tr>
<td>Pectin</td>
<td>Wine</td>
<td>Grain</td>
<td>Straw</td>
<td>Landfill leachate</td>
</tr>
<tr>
<td>Citric acid</td>
<td>Coffee</td>
<td>Fruit</td>
<td>Bagasse</td>
<td>Acid mine water</td>
</tr>
</tbody>
</table>

- Yeast, Italy
- Beer, Brazil
- Distillery, Japan
- Paper, Netherlands
- Chemical, Netherlands
Full scale example: Brewery Effluent

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>Brewery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>m³/d</td>
<td>2720 – 5780</td>
</tr>
<tr>
<td>COD average</td>
<td>mg/l</td>
<td>4043</td>
</tr>
<tr>
<td>COD range</td>
<td>mg/l</td>
<td>2020 – 5790</td>
</tr>
<tr>
<td>SS</td>
<td>mg/l</td>
<td>260 – 2160</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>21 – 40</td>
</tr>
<tr>
<td>PH</td>
<td></td>
<td>2.6 – 7.0</td>
</tr>
</tbody>
</table>

COD-load: 17 ton/day
Required reactor dimensions:
V = 500 m³ only, h = 25 m, d = 5 m
Brewery effluent: Energy benefit!

Energy content 1 ton COD \( \approx 13.5 \text{ GJ} \approx 3.8 \text{ MWh} \)

Energy recovered:
17 ton COD x 0.85 (eff) x 3820 kWh** x 40% CHP eff. 
= 22 MWh-e/day \( \approx 1 \text{ MW powerplant} \)

No energy consumption:
Average energy requirement activated sludge: \( \approx 1 \text{ kWh-e/kg COD removed} \)
Saved: 17 ton COD x 0.85 (eff.) 
= 15 MWh-e/day

Total energy benefit:
22 + 15 = 37 MWh-e/day
\( \cong 3300 \text{ €/d (with 0.09 €/kWh)} \)
\( \cong 1.2 \times 10^6 \text{ €/year} \)
Brewery effluent: CO₂ emission reduction!

Energy recovered:
17 ton COD x 0.85 (eff) x 3820 kWh** x 40% CHP eff.
= 22 MWh-e/day ≈ 19 ton CO₂ reduction/day (coal)

No energy consumption:
17 ton COD x 0.9 (eff.) = 15 MWh-e/day
≈ 13 ton CO₂ reduction/day (coal)

Total CO₂ emission reduction:
19 + 13 = 32 ton CO₂ /day

≈ 380 €/d (with 20 €/ton CO₂)
≈ 140.000 €/year
## Energy output and CO$_2$ emission reduction using AD systems

### 2008 state-of-the-art

<table>
<thead>
<tr>
<th>Category</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading capacity (kg COD.m$^{-3}$.d$^{-1}$)</td>
<td>10 – 35</td>
</tr>
<tr>
<td>Energy output (MJ.m$^{-3}$ reactor installed.d$^{-1}$)</td>
<td>55 – 390</td>
</tr>
<tr>
<td>Electric power output (kW-e.m$^{-3}$ reactor installed)</td>
<td>0.25 – 1.7</td>
</tr>
<tr>
<td>CO$_2$ emission reduction (tonCO$_2$.m$^{-3}$.y$^{-1}$, compared to coal-driven power plant)</td>
<td>1.9 – 13</td>
</tr>
</tbody>
</table>

### Assumptions:
- 80% CH$_4$ recovery relative to influent COD load
- 40% electric conversion efficiency using a modern combined heat power (CHP) generator
- Intermediate values are obtained by linear interpolation.
Energy recovery & CO₂ credits as an incentive to implement environmental technologies in developing countries?

Treatment alcohol distillery effluents Cuba (Santa Clara):
- 800 m³.d⁻¹,
- 65 kg COD.m⁻³

**Anaerobics:** 13,500 m³ CH₄.d⁻¹
or: about **2.2 MW-electric** (40% eff.)
At a price of 0.12 US$ .kWh⁻¹ this equals: **2.300.000 US$.y⁻¹**
**CO₂ credits:** 330.000 US$.y⁻¹ (coal)
More energy from “end-of-the-pipe” to “zero-discharge”

- 1000 ton/d paper
- 1050 ton/d stock
- fresh water 1000 m³/d
- evaporation 1000 m³/d
- 80 ton/d steam
- 9000 m³/d biogas
- 4000 m³/d anaerobic
- 4000 m³/d aerobic
- 1 ton/d waste sludge
- 55 °C
- 35 °C

Energy savings:
- no effluent 1045 MJ/ton (115 MWh-e/dag)
- anaerobics 200 MJ/ton (22 MWh-e/dag)

- H₂S removal
- sulfur 0.2 ton/d
- corrugated card board industry

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Anaerobics as “kidney technology”?

1. How to cope with more extreme conditions?:
   - Accumulation of toxic / recalcitrant compounds
   - Temperature increase (thermophilic)
   - Salinity increase (Na<sup>+</sup>)

2. Biofilm/granule stability guaranteed?
3. Integration with complementary technologies?

- Adapting / optimising sludge bed systems?
- Alternative anaerobic technologies?
High salinity decreases granule stability!

**Ca^{++}** extraction by **Na^{+}**

Ismail et al., Wat. Sci. Technol., 2008

Granule Strength Decrease after 6 months of UASB operation

EDX analysis: Ca^{++} distribution in Shell sludge
Anaerobic MBR technology for extreme conditions?

Application potential:
- when sludge immobilisation is not likely (high temperatures, high salinity, fluct. pH)
- presence of recalcitrant compounds (spec. bacteria)
- high solids concentrations
- other extremes?
Impact of temp. on achievable membrane flux

**Submerged MBRs, VFA as substrate**

(Jeison and van Lier, J. of Membr. Sci., 2006)
Flux determining factors in anaerobic MBRs


Critical flux (L/m² h)

Time (d)

Thermophilic

Mesophilic

Particle deposition

Smaller particle size

High shear rate

The shear rate dilemma...
(Re)source oriented sanitation concepts (Desar):

MDG can not be reached! 2008: UN year of sanitation

Water quantity (l/d)

1.2 + 35
100
85

Black water
Urine
Grey water
Rain water

AD in Desar:
- sludge stabilisation
- nutrients production
- energy production
- scavenger micropollutants
Resources from domestic wastewater?

Water quantity (l/d)

- 1.2 + 35
  - Black water
  - Urine
- 100
  - Grey water
- 85
  - Rain water

Urine + faeces = 1.2 l/pers./day !!

Urine + faeces + kitchen waste:
- 1.5 l in volume
- 91 % N
- 69 % P
- 70 % COD
- Pathogens
- salts
- micro pollutants

Recovery of energy & nutrients feasible
Grey water for irrigation!!
Black water treatment: Sneek

- Black water vacuum toilets
- UASB (ST)
  - CH₄
  - Mg⁺⁺
  - MgNH₄PO₄
  - N₂
- Struvite (MAP) precipitation
  - MAP (fertilizer)
  - Sludge (return UASB)
- Autotrophic N removal (OLAND)
- Final polishing
- Discharge to surface water

Stabilized sludge (reuse?)

Table:

<table>
<thead>
<tr>
<th>Process</th>
<th>HRT min</th>
<th>T max</th>
</tr>
</thead>
<tbody>
<tr>
<td>UASB (ST)</td>
<td>7d</td>
<td>30°C</td>
</tr>
<tr>
<td>Struvite</td>
<td>t contact</td>
<td>30min</td>
</tr>
<tr>
<td>N-removal</td>
<td>HRT min</td>
<td>3.5d</td>
</tr>
</tbody>
</table>

Zeeman et al., Wat.Sci.Technol., 2008
# Energy balance of the Sneek concept:

<table>
<thead>
<tr>
<th>Utility</th>
<th>Energy</th>
<th>Energy in MJ\textsubscript{electric}.p\textsuperscript{-1}.year\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biogas production</strong>&lt;br&gt;(black/grey water,&lt;br&gt;kitchen waste)</td>
<td>Waste(water) treatment&lt;br&gt;10,5 m\textsuperscript{3} CH\textsubscript{4}.p\textsuperscript{-1}.y\textsuperscript{-1}&lt;br&gt;= 374 MJ.p\textsuperscript{-1}.y\textsuperscript{-1}</td>
<td>131</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td>Vacuum transport&lt;br&gt;25 kWh.p\textsuperscript{-1}.y\textsuperscript{-1}</td>
<td>-90</td>
</tr>
<tr>
<td></td>
<td>Kitchen waste grinders&lt;br&gt;-5 kWh.p\textsuperscript{-1}.y\textsuperscript{-1}</td>
<td>-18,0</td>
</tr>
<tr>
<td></td>
<td>Post- treatment</td>
<td>-43</td>
</tr>
<tr>
<td><strong>Energy saving</strong></td>
<td>STP&lt;br&gt;24 kWh.p\textsuperscript{-1}.y\textsuperscript{-1}</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Conventional sewer&lt;br&gt;30 kWh.p\textsuperscript{-1}.y\textsuperscript{-1}</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>Drinking water&lt;br&gt;0.5 kWh.m\textsuperscript{3}\textsubscript{produced}</td>
<td>26</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

Zeeman et al., Wat.Sci.Technol., 2008
Domestic wastewater as a resource (Sneek results):

Total energy savings in Sneek: 200 MJ.person\(^{-1}\).year\(^{-1}\)

\textit{Extrapolating to the Netherlands: 915 million kWh/year}

\[
\approx 100 \text{ MW}
\]

\[
\approx 200,000 \text{ 4-persons households}
\]

Nutrients: 0.14 kg P.person\(^{-1}\).year\(^{-1}\)

or: 2.310 ton P.year\(^{-1}\) as struvite (\(\text{NH}_4\text{MgPO}_4\))

Potentially reusable grey water:

90 l.person\(^{-1}\).year\(^{-1}\)

\[
\approx 540 \text{ million m}^3\text{.year}^{-1} \text{ in NL}
\]

\[
\approx (8-11 \text{ million ha irrigated area.})
\]

\textbf{Available' phosphorus reserves (%)}

\begin{itemize}
\item 2\% growth
\item 2.5\% growth
\item 3\% growth
\end{itemize}

Source: Driver et al. (2001)
AD sanitation potentials for developing countries?

- prevent diseases
- prevent water pollution
- protect drinking water source
- produce nutrients
- produce energy
Community on-site bio-digester toilet blocks in Kibera, Kenia
Conclusions

- AD is consolidated technology for wastewater treatment

- Energy efficiency and actual energy recovery is a driver of increasing importance!... 1 ton COD ≈ 13.5 GJ....

- AD needs adaptation to more extreme environments! Need for stable sludge bed systems, anaerobic MBR, other?

- AD may play a prominent role in sustainable sanitation approaches coupling: hygiene, disease prevention, energy recovery, production of fertilisers, protection water resources/environment.
Thanks to all colleagues, PhDs and research fellows

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Direct scavenging of electrons

Wastewater → Anaerobic cell → Organic matter conversion → Anode

[CH₂O] + H₂O → CO₂ + 4H⁺ + 4e⁻

Ion selective membrane

Cathode

O₂ + 4H⁺ + 4e⁻ → 2H₂O

Aerobic cell Water reduction

Clean water → Blaärobe cel

Belatibting (O₂)
Biomass cascading in alcohol distilleries, Brasil

Van Haandel, 2004
Van Haandel & Van Lier, 2006

1 m³ = 800 kg Alcohol
0.25 MWh Power
0.5 MWh Power

DISTILLATORY

CH4 100 kg
UASB
settler
dryer

Generator
boiler
dryer

Generator

steam
heat

1.2 m

100 cane 13 t

48 bagasse

40

3.5

7

Van Haandel, 2004
Van Haandel & Van Lier, 2006

Output without AD of wastes
= 5 m³ EtOH/ha
= 4 ton EtOH
= 40% cane energy

= percentage of cane energy

SUGAR CANE FIELDS
(1/5 ha)

water sunlight limestone
CO₂

nutrients
Optimised energy output alcohol distillery:
(using all by-products)
- Heat (steam production for local use)
- Surplus Electric (35% eff.): 6.3 MWh-e/(ha.y) ($\approx$ 0.7 kW/ha)
- Liquid: alcohol: 5 m$^3$/y
  alcohol price (2006): 400 US$/m$^3$ ($\approx$ 300 €/m$^3$)
Total economic benefit: 1500 + 630 = 2130 €/(ha.y).

Full digestion of cane: 24 MWh-e/(ha.y) $\approx$ 2.8 kW/ha
50 % digestion eff. of solid fraction
Non-digestable fraction is incinerated
At 0.10 €/KWh-e: 2400 €/(ha.y)
Bio-methanation of energy crops: sustainable contribution?

Generally: 0.5 – 1.5 MW-e HRT up to 90 days…
AD reactor not the biggest concern:
- raw materials
- logistics
- maximising energy recovery
- digestate application
- etc.
Energy balance of energy crop digester

Resch, Braun and Kirchmayer, 2007. BOKU, Austria

- subsidies: up to 0.22 Euro/kWh
- renewable energy
- carbon credits

Maiz