NEWgenerator™

membrane biotechnology for the recovery of nutrients, energy and water from human wastes

nutrients energy water

Int'l Faecal Sludge Management Conference 2 (FSM2)

Oct. 29-Nov. 1, 2012
Durban, South Africa

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Acknowledgement

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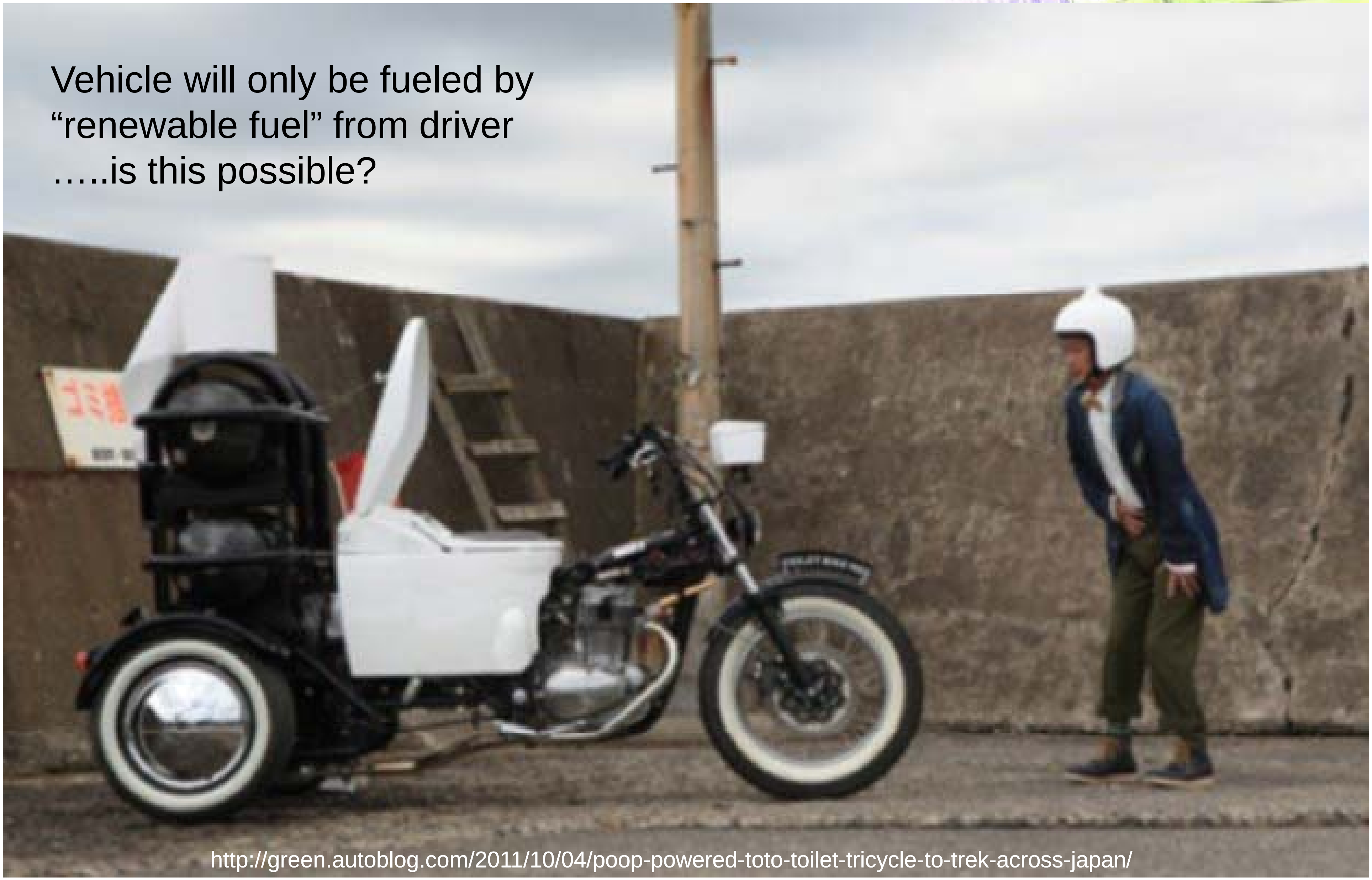
  - Herby Jean, USF

nutrients energy water


I POOPED TODAY!
TRUST ME
I'M A
NINJA!

Oct 2011 - Toilet mfgr TOTO announces toilet-powered vehicle to trek across Japan



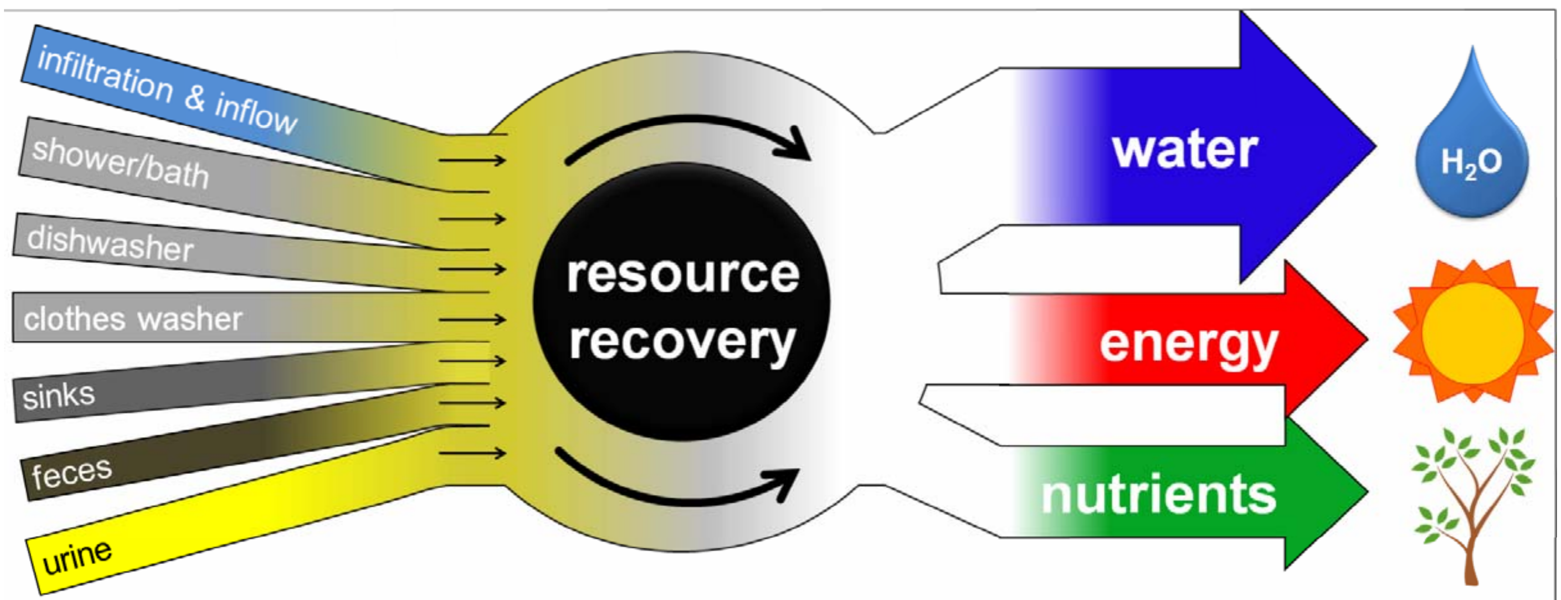
Vehicle will only be fueled by
“renewable fuel” from driver
…..is this possible?

http://green.autoblog.com/2011/10/04/poop-powered-toto-toilet-tricycle-to-trek-across-japan/

Wastewater as a renewable resource

A paradigm shift is underway!

http://www.sustainlane.com/reviews/getting-the-most-from-human-waste/ICF8A2T14UAQ9HTV27Q8VLQXRTOI



Graphics: Jeremy Guest

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From 1950's Sewage Treatment Primer

" It is true that there are recoverable constituents in sewage, but, like the extraction of gold from seawater, the process of recovery is more costly than the value of the recovered constituents."

Babbitt, H. E. (1953). *Sewage and Sewage Treatment*, John Wiley & Sons, Inc., New York.

Technology needs for achieving MDGs

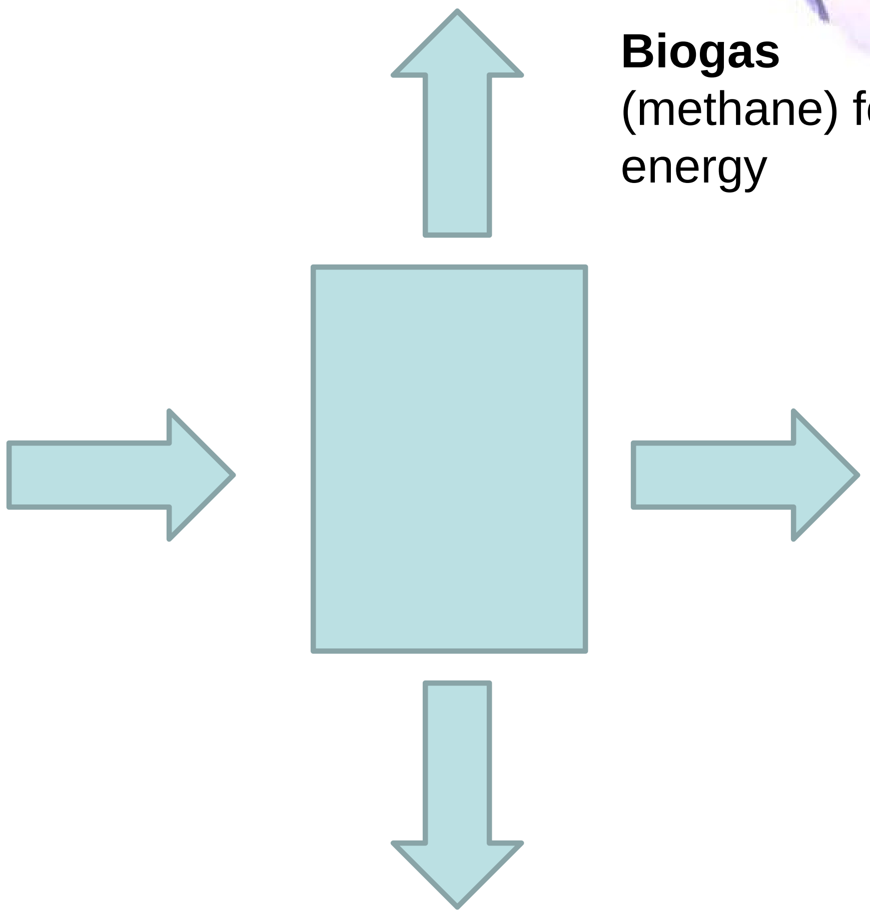
- Robust
  - able to remove multiple contaminants in single unit without a series of complicated unit processes
- Cost-effective
- Easy to implement
- Simple enough for general public to use and operate
- Low energy requirement
- Low maintenance (easy to repair)
- Long-lasting
- Context-specific responses (demand-driven), culturally appropriate
- Help build capacity
- Often, decentralized or onsite treatment are needed
- Focus on **RESOURCE RECOVERY**, not just removal

- Need for invention of **new** and sustainable technologies, not just simplification of existing technologies

NEWgenerator^{TM} process

Domestic mixed faecal sludge wastes (feces, urine, flush water, wash water) + other organic wastes (e.g., food waste, livestock waste)

Biogas (methane) for energy



Membrane filtered liquid fertilizer (fertigation), microbially safe

Solid fertilizer for soil conditioner (disinfected and stabilized)

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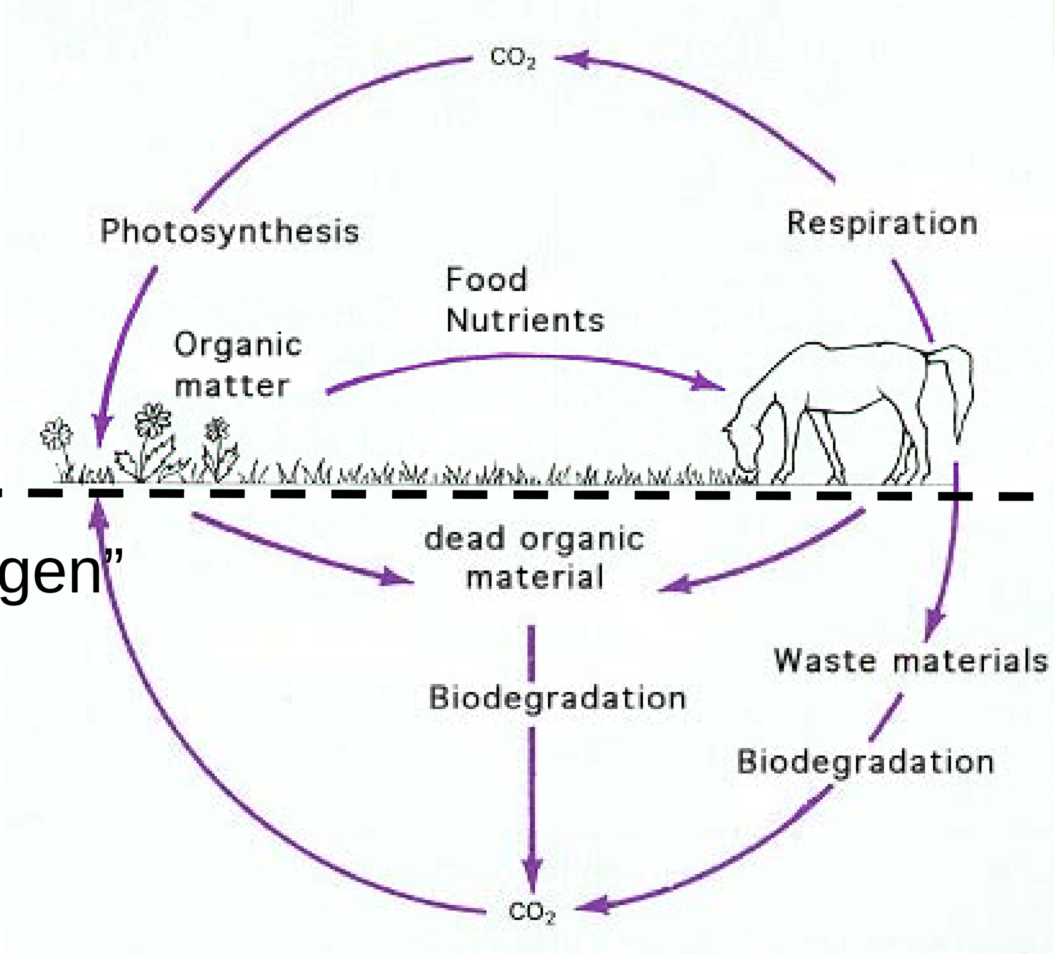
The Carbon Cycle

Aerobic – “with oxygen”

Anaerobic – “without oxygen”



Energy potential in wastes and wastewater

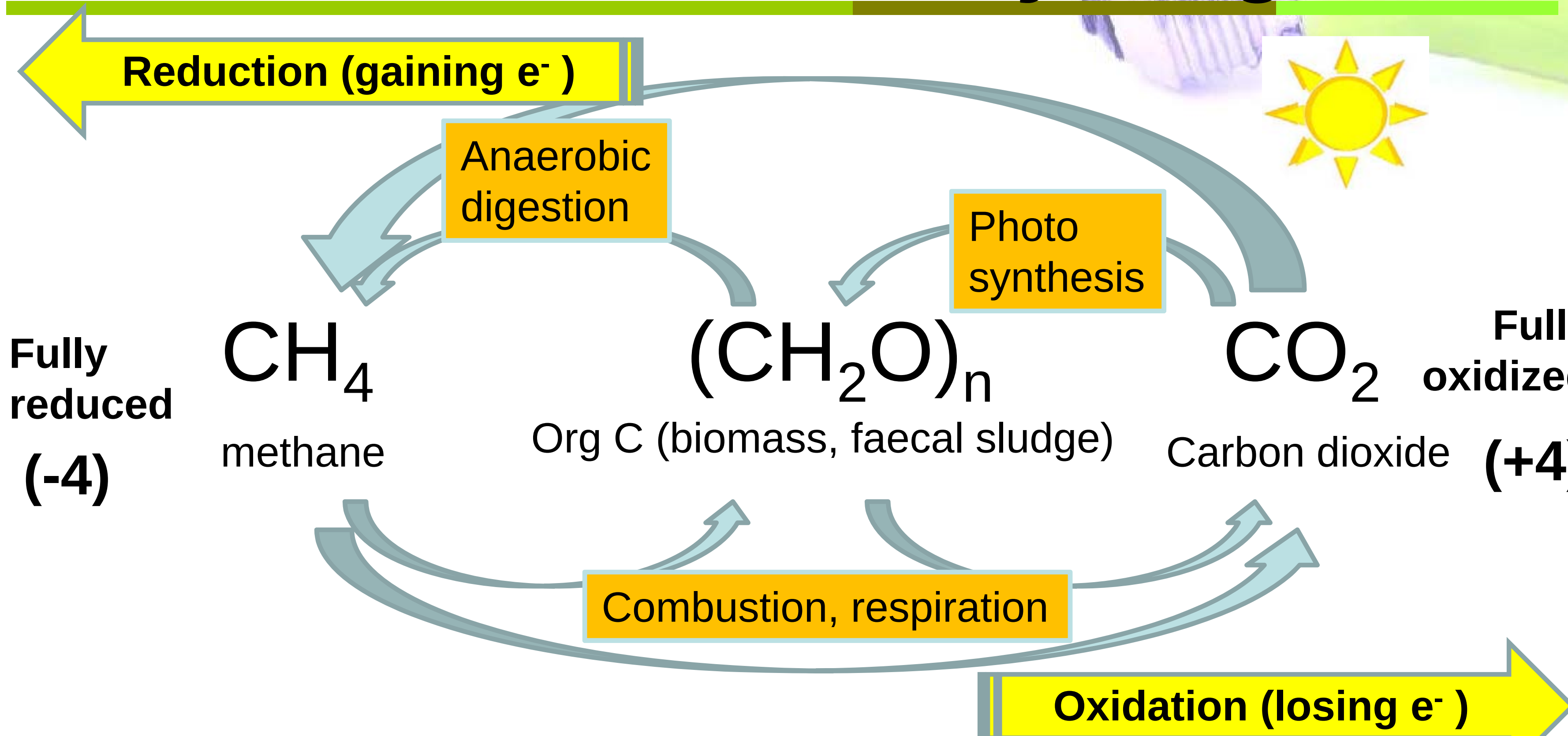
Waste organic matter = Reservoirs of energy

View **chemical oxygen demand (COD)** as energy potential, rather than pollution

The **choices** lie in how we recover this potential energy

Further, how sustainable are the choices?

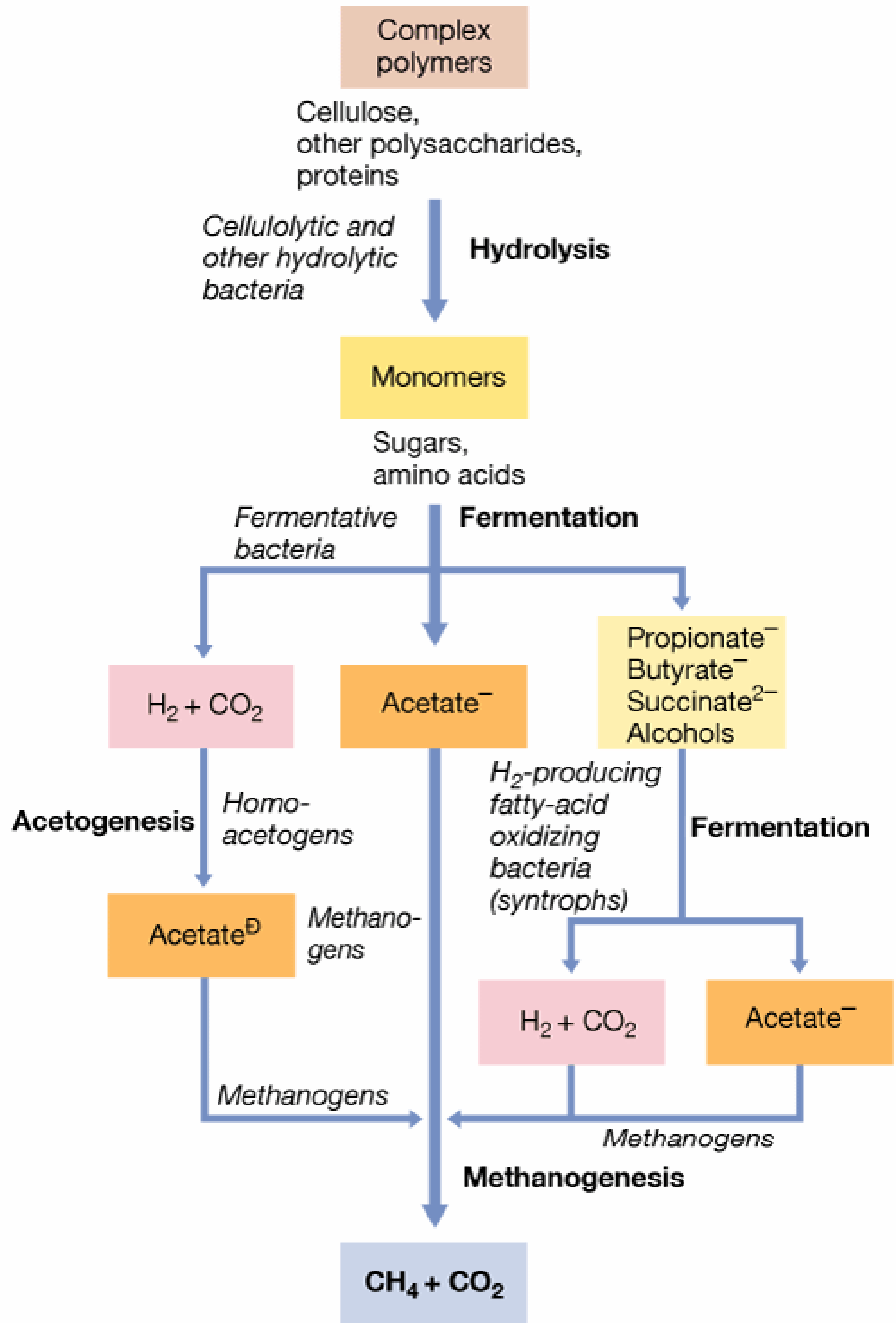
Energy states of carbon all about **BioRecycling**



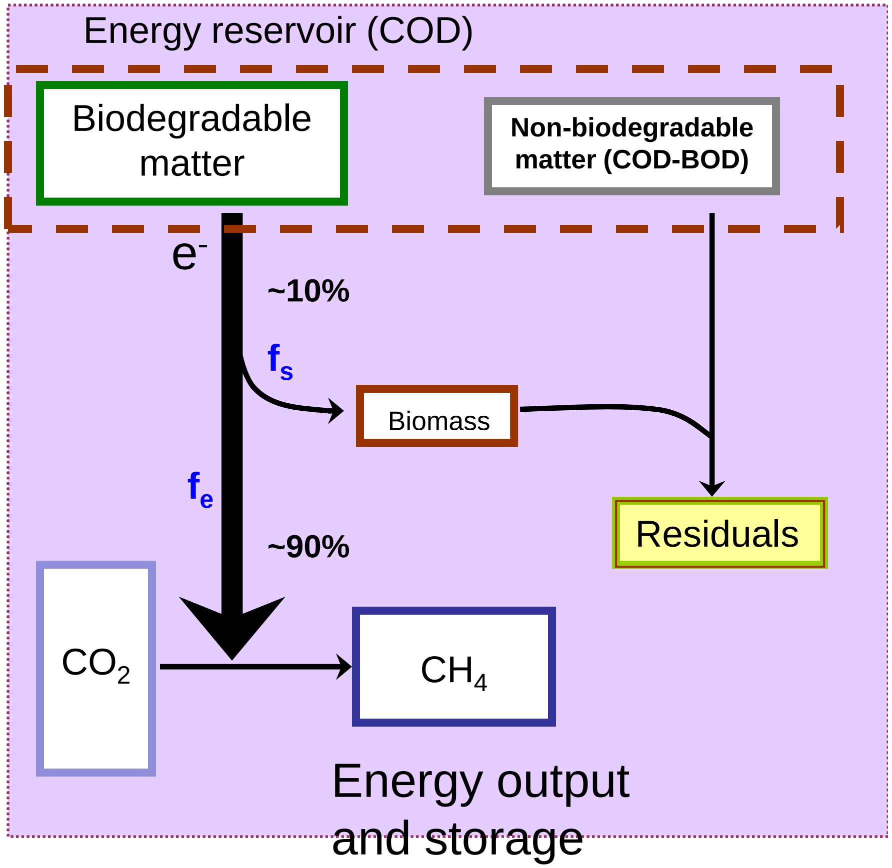
	Methane	biomass	Carbon dioxide
Energy	rich	moderate	none
Redox state	-4	In between	+4
COD (energy)	4 g OD/g (180.4 Wh /g)	Typically 1-3 g OD/g	zero

Popular saying in the 80's

Waste organic matter as e⁻ donor



Anaerobic



Flow of carbon and electrons in anaerobic digestion

Note: The chemical potential energy of degradable organics is completely transferred to methane

Energy is efficiently captured in biogas

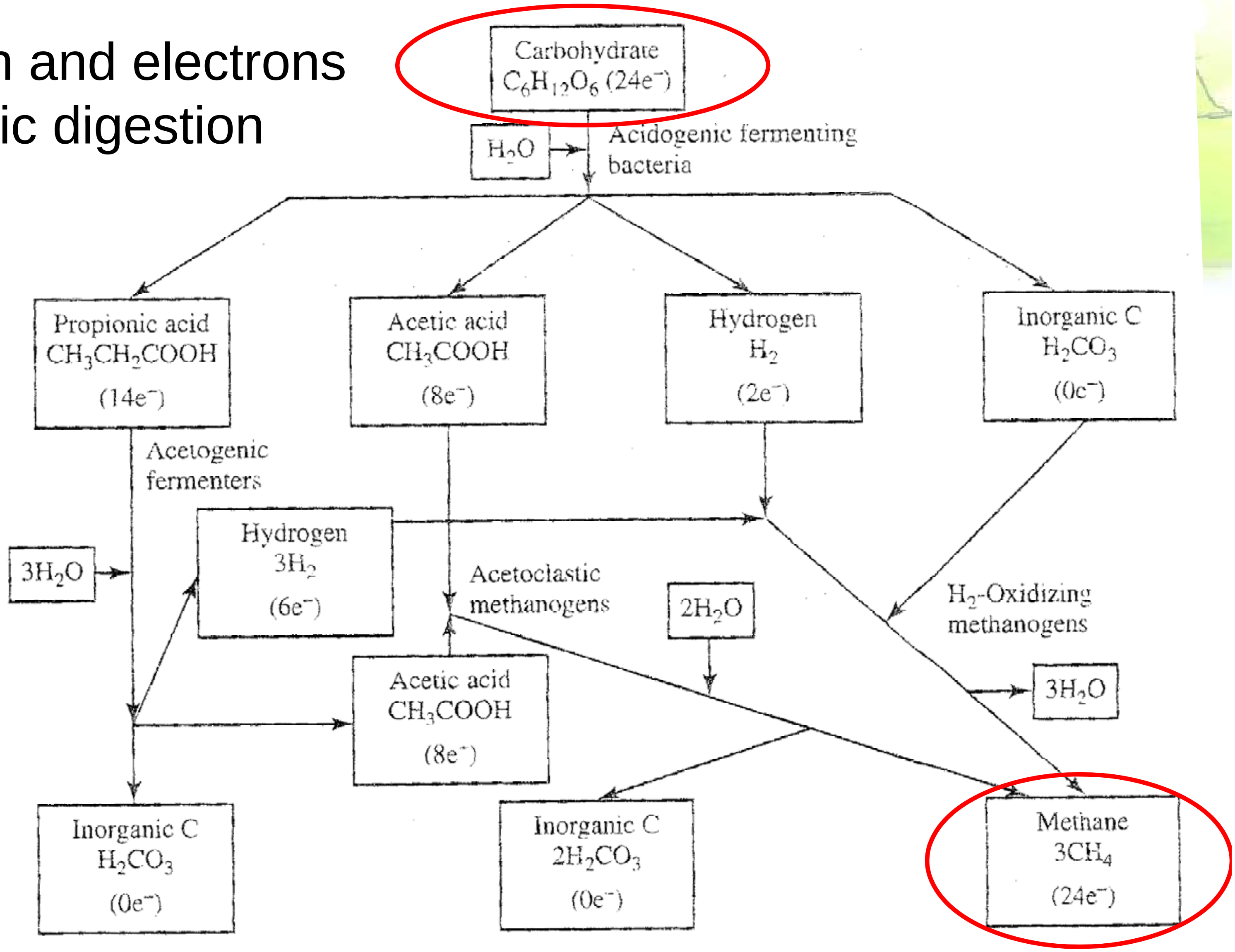


Figure 1.40 Flow of intermediate molecules in an anaerobic ecosystem that starts with carbohydrate, forms intermediate organic acids and H_2, and ultimately generates CH_4. The net reaction is $C_6H_{12}O_6 + 3\,H_2O \rightarrow 3\,CH_4 + 3\,H_2CO_3$, but four unique microbial groups are involved.

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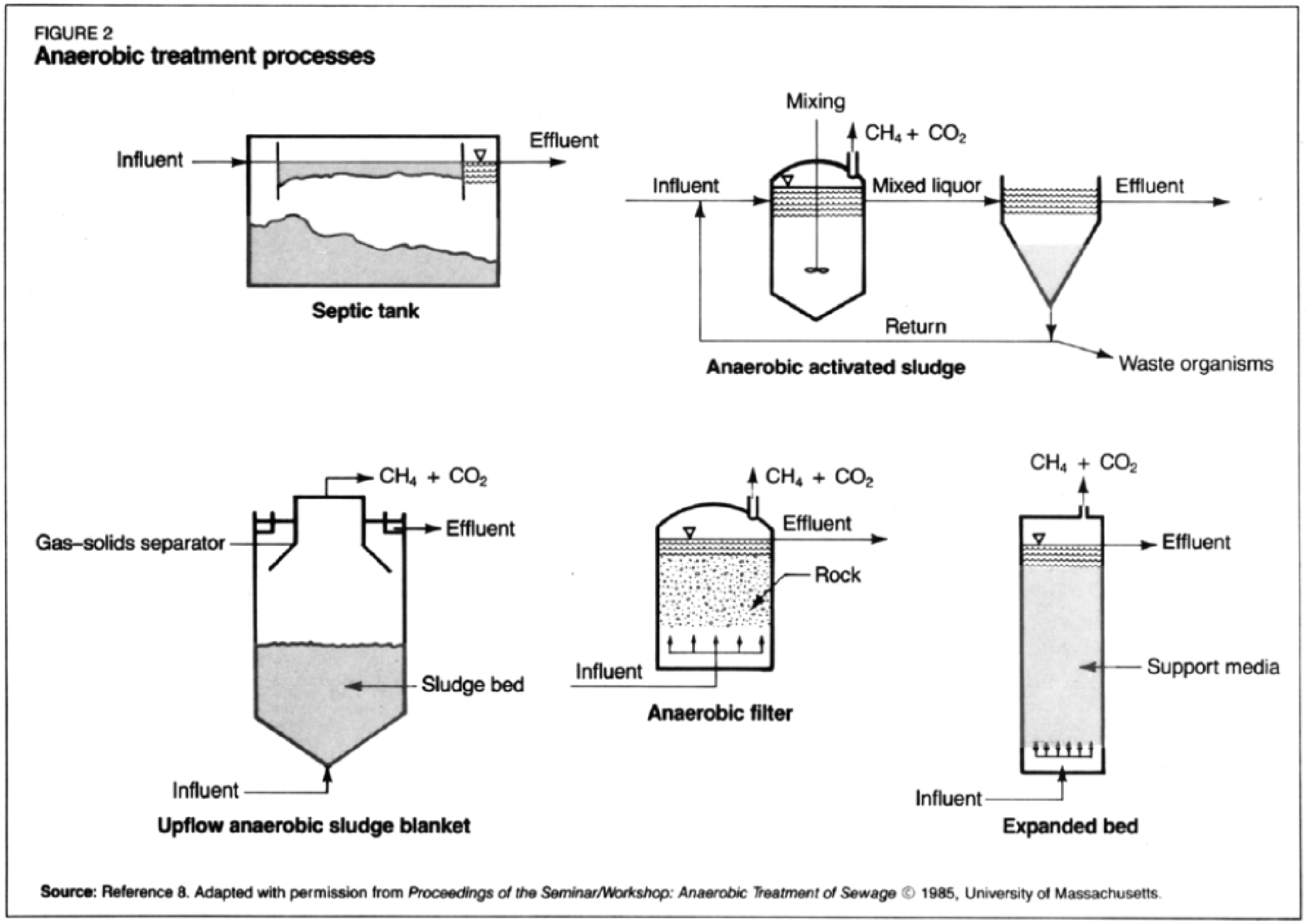
Energy content of WW and Wastes

- Municipal WW in the US is very dilute (500 mg/L COD), yielding est.1.74 kWh/m^3.
- Faecal sludge pits contain much more energy per m^3.

Source	COD (mg/L)	kWh/m^3 (max)	kWh/m^3 (@25%)
Municipal WW	500	1.74	0.44
Household WW	850	2.96	0.74
Industrial (ex)	5000	17.4	4.4
Agricultural (ex)	10,000	34.8	8.7
Landfill leachate (young)	20,000	69.6	17.4

Ex. of anaerobic processes for sewage treatment



 From William Jewell (1987)

The Sulabh Expirience (India)

- The biggest public toilet in the world has been constructed at Shirdi (India).
- 120 WCs, 108 bathing cubicles, 28 special toilets and other facilities coupled with a biogas generation system.
- Biogas used for different purposes
  - Electricity generation,
  - Lighting of lamps,
  - Cooking
  - Heating in winter seasons



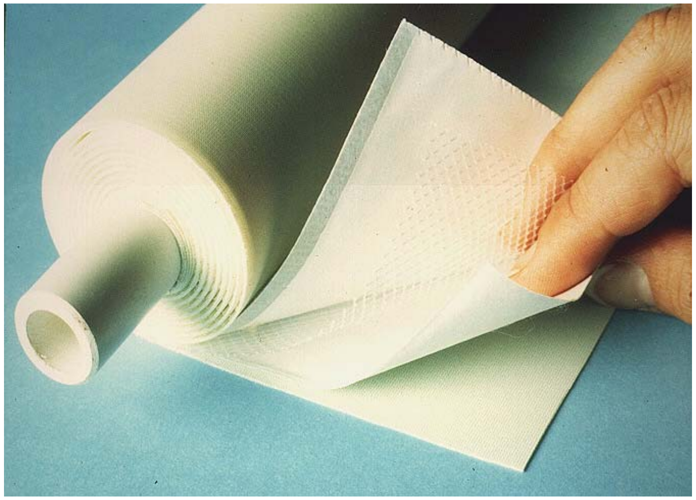
Limitations of anaerobic waste treatment

- Many techniques developed over the centuries
  – Septic tank, baffled reactor, UASB, digester, etc.
- Effluent contains nutrients, however….
- …Concerns over direct reuse due to pathogens.
  – Gravity settling cannot remove colloids!
- Potential for washout of solids and microbes from hydraulic overloading → need to slow it down

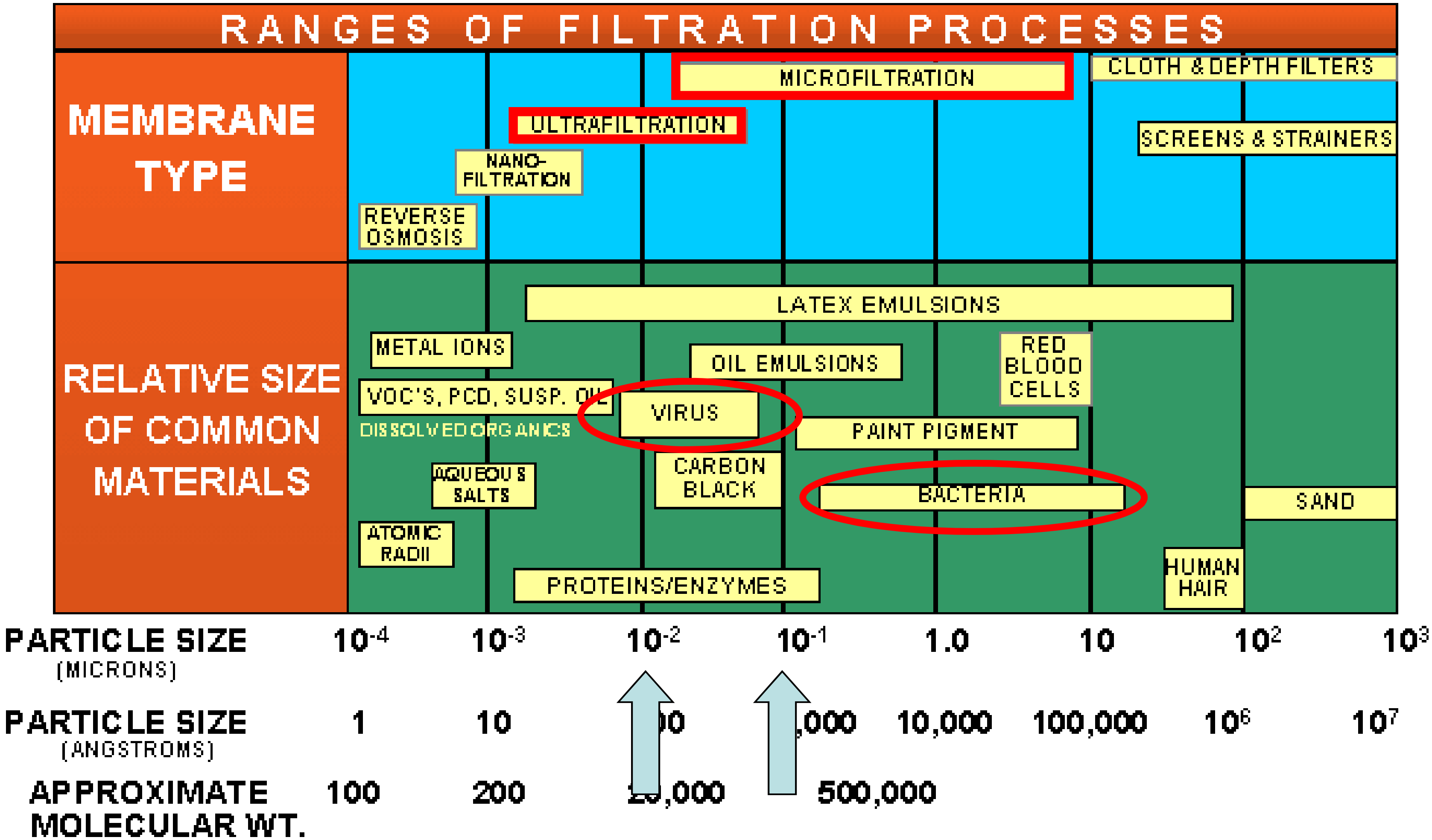
- Need for complete separation of colloids and liquid

Promise of Membrane technology

- A membrane is **barrier**, generally a thin polymeric film, whereby only select substances can pass (e.g., clean water) but impurities (salt, contaminants, bacteria, dirt) are rejected.
- Uses:
  - Desalination
  - Water purification
  - Wastewater treatment
  - Medical (e.g., artificial kidney)



Filtration Spectrum



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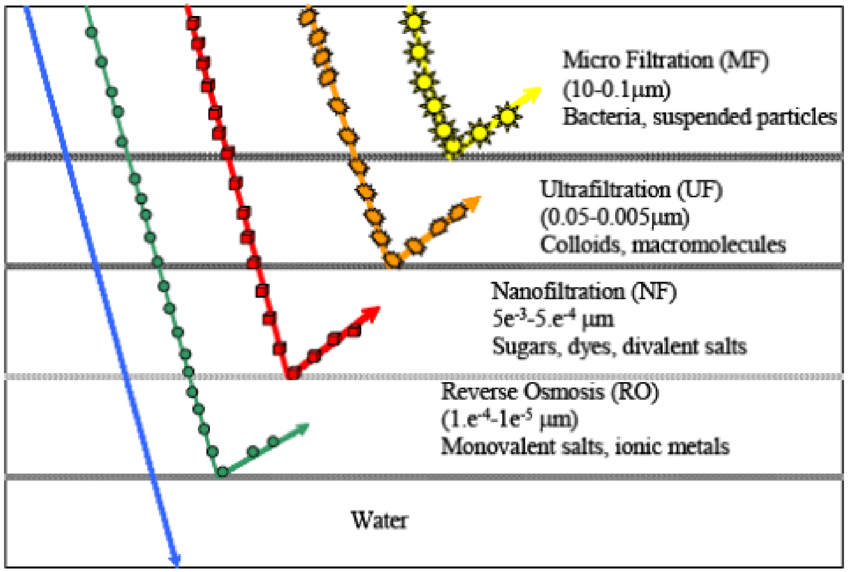
Rejection by membrane

Membranes provide an absolute physical barrier for pathogen removal for safe dewatering



Font and Garcia

Helminths (Ascaris) eggs (35μm)

Helminths (Ascaris) eggs (35μm)

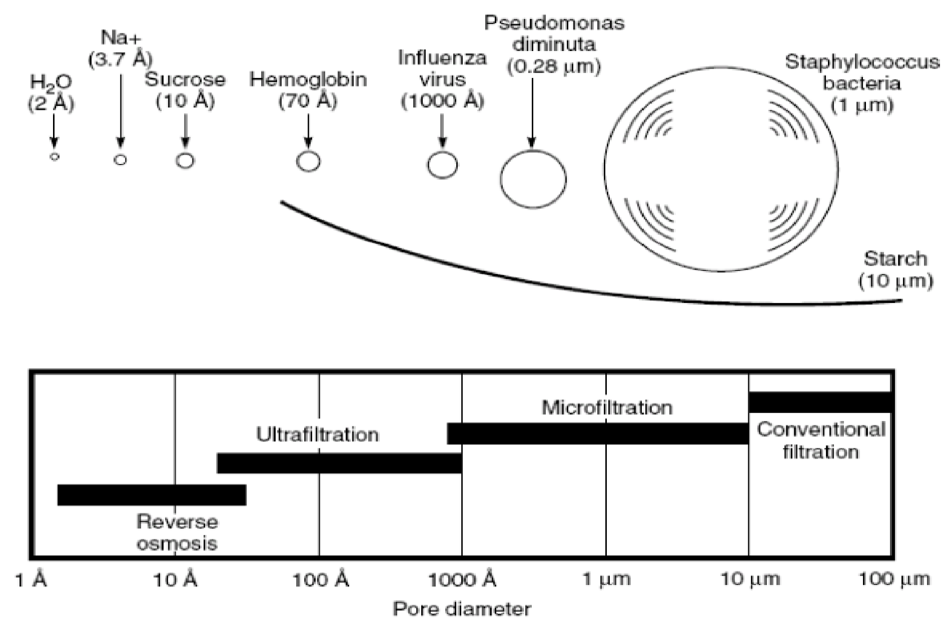


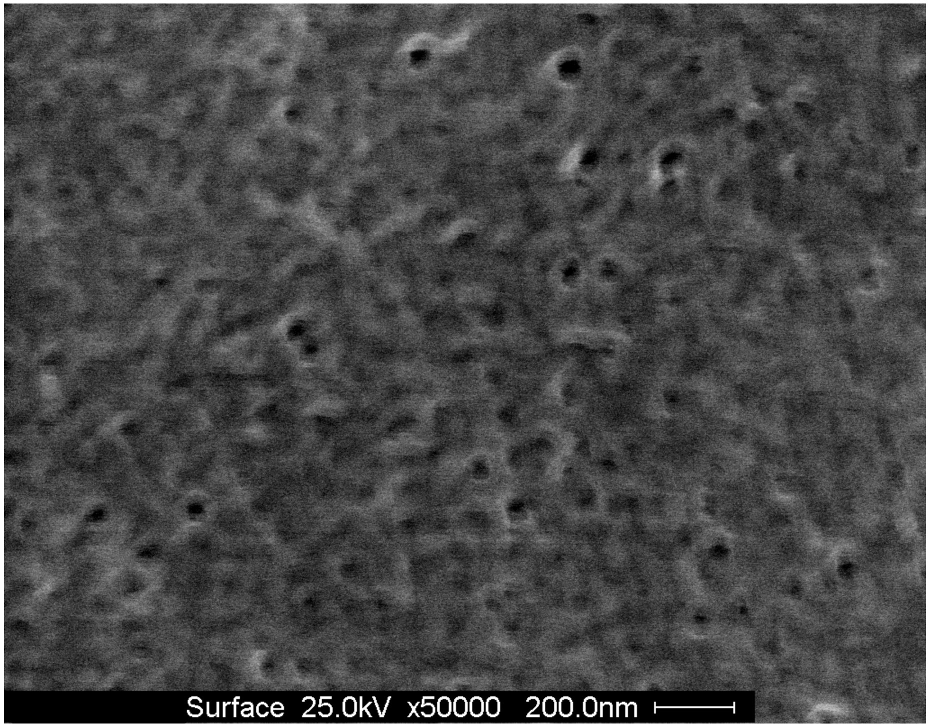
Figure 1.2 Reverse osmosis, ultrafiltration, microfiltration, and conventional filtration are related processes differing principally in the average pore diameter of the membrane filter. Reverse osmosis membranes are so dense that discrete pores do not exist; transport occurs via statistically distributed free volume areas. The relative size of different solutes removed by each class of membrane is illustrated in this schematic

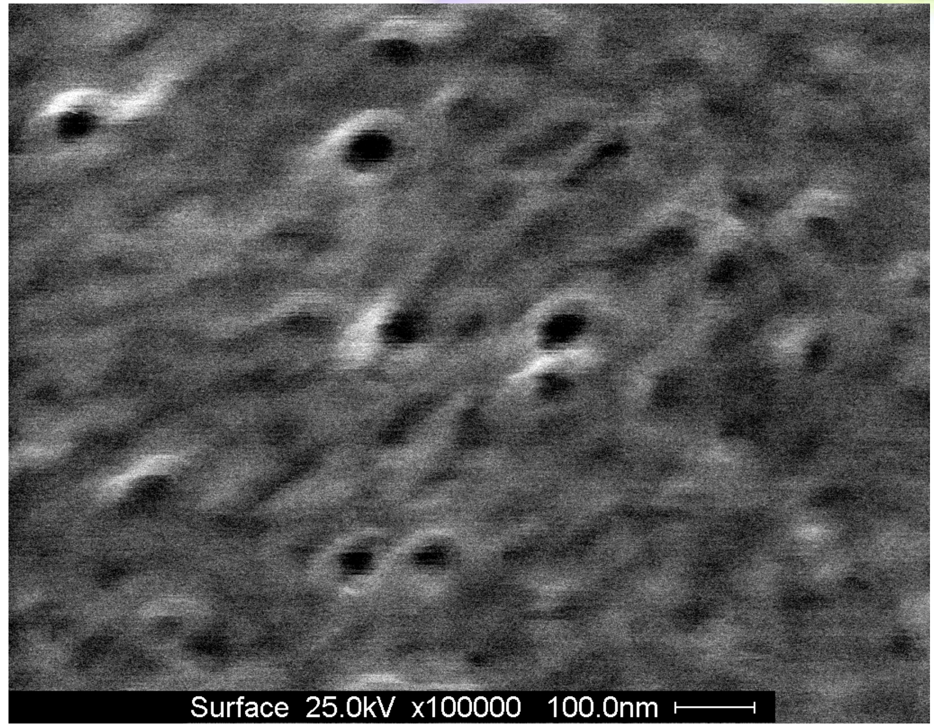
Baker (Ch. 1)

UF Membrane

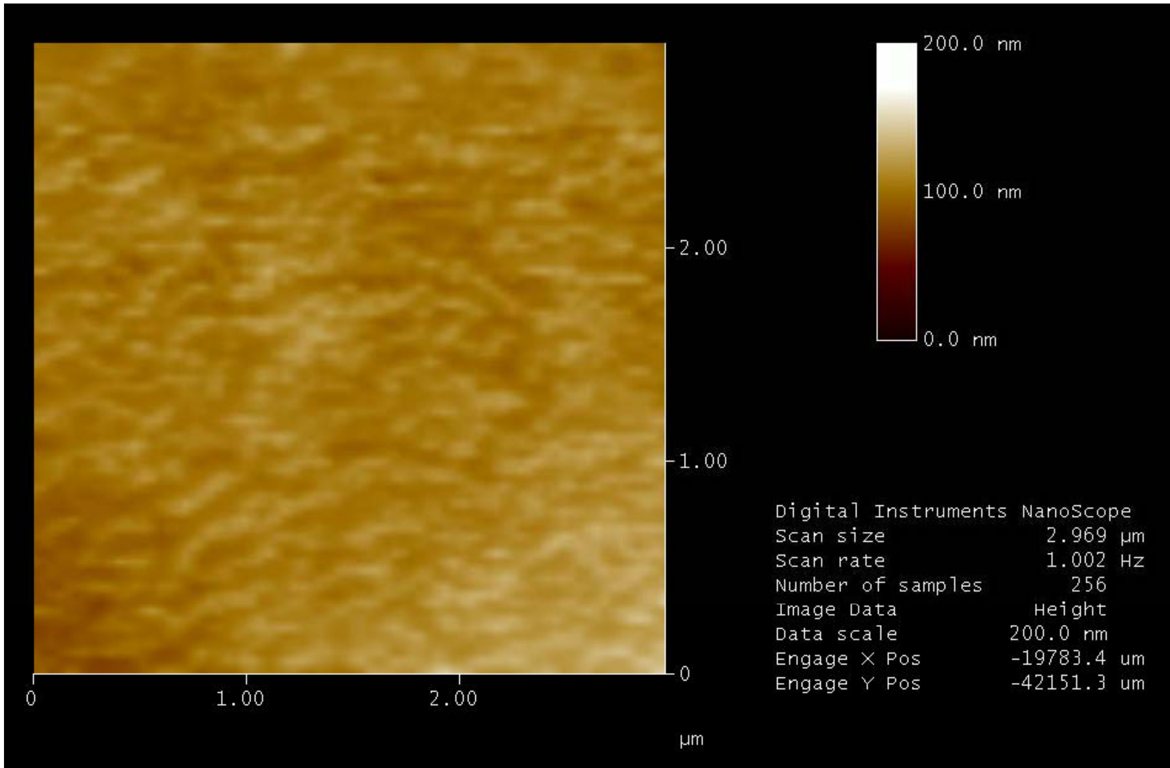
Pathogen	Log removal
Helminths	8 (99.999999%)
Bacteria	6 (99.9999%)
Viruses	4 (99.99%)

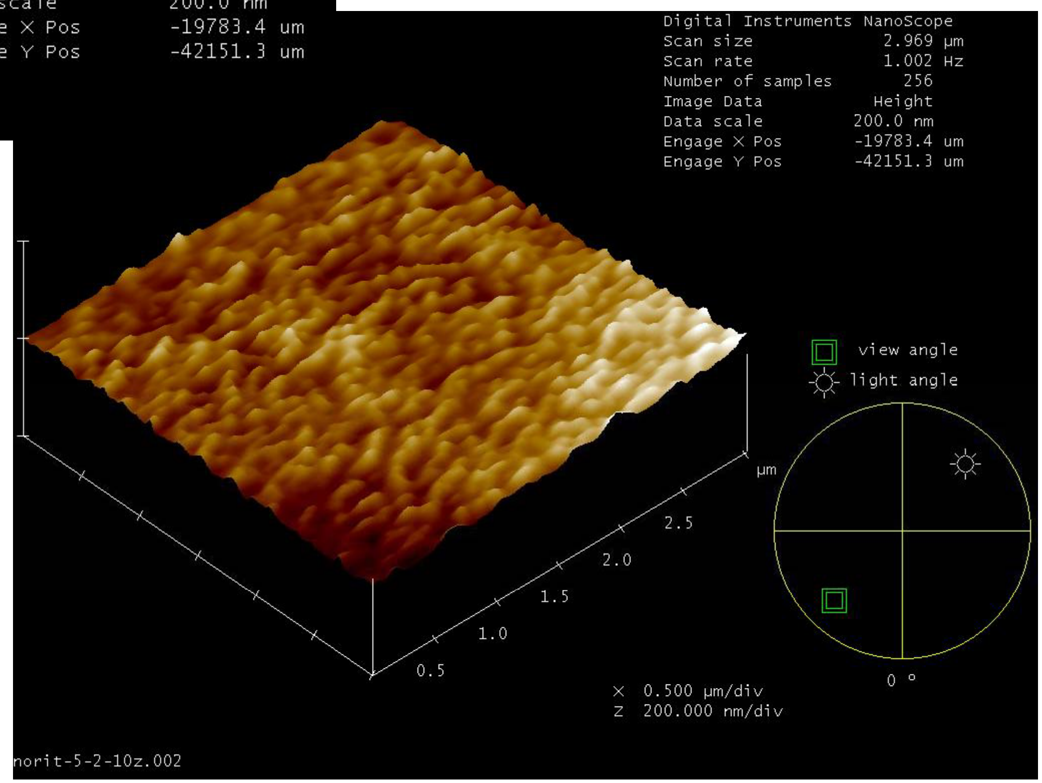
UF Membrane Surface





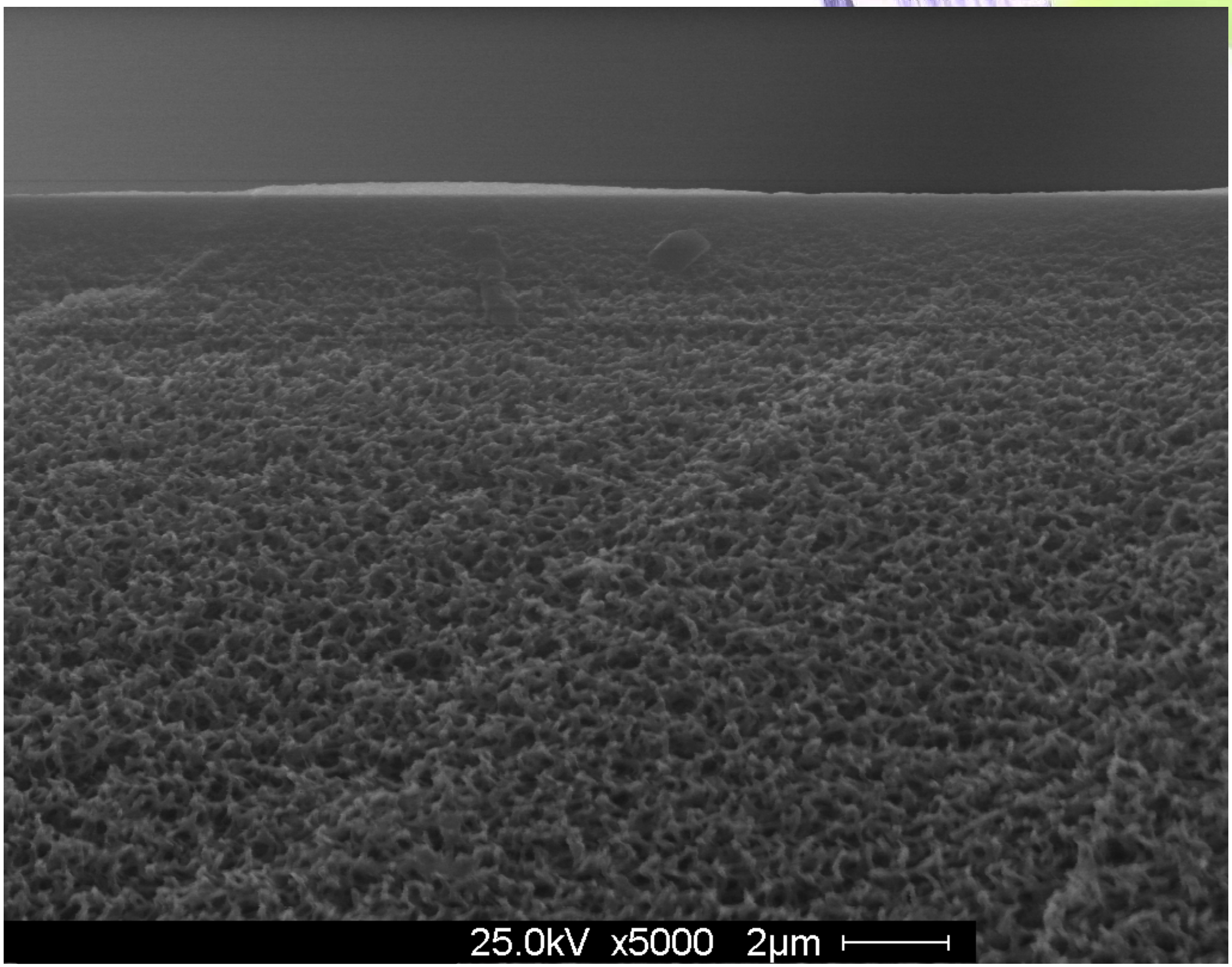
- Average pore size: 0.03 um





Atomic force microscopy image of UF membrane surface (200 nm scale)

UF Membrane cross-section (5000X)



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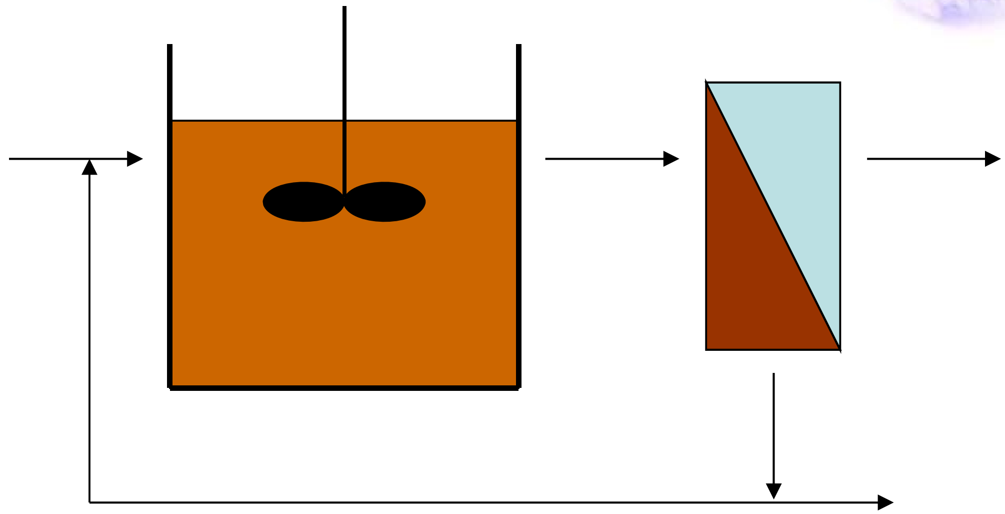
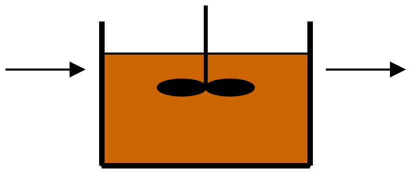
What is a membrane bioreactor?



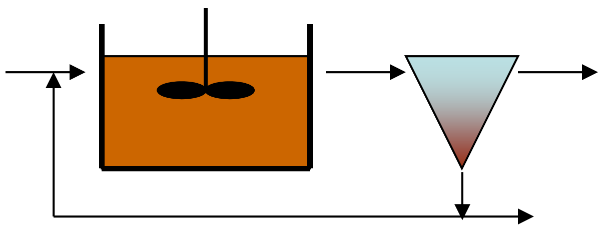
- Coupling of membrane and biological processes, where membrane separation and biological conversion of substrate occur **synergistically** to achieve results not possible (or at least feasible) by each process alone.

Premise of solid/liquid separation MBRs for WWT



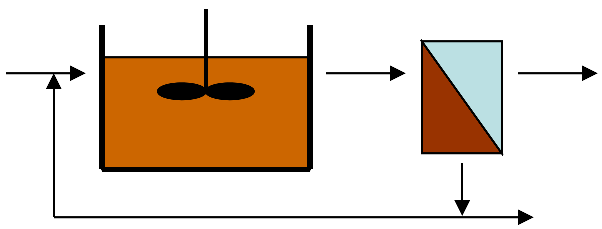
$VSS_{reactor}$ = 200 mg/L

$VSS_{effluent}$ = 200 mg/L



$VSS_{reactor}$ = 4,000 mg/L

$VSS_{effluent}$ = 10 mg/L



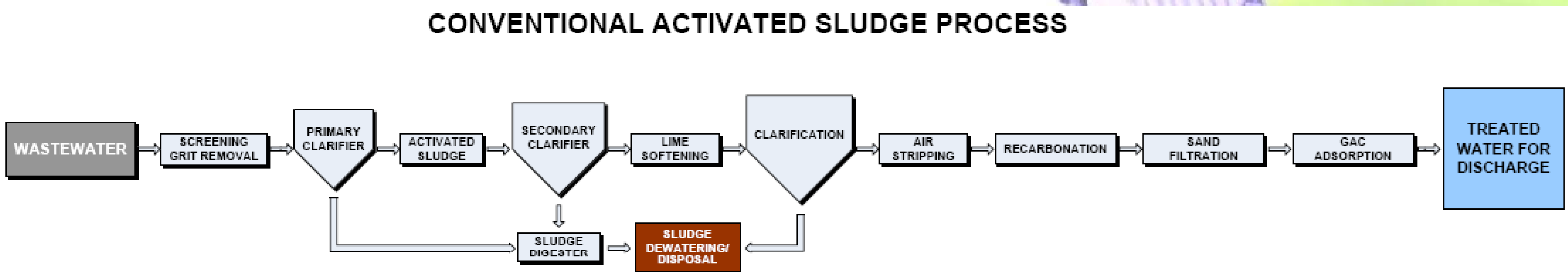
$VSS_{reactor}$ = 20,000 mg/L

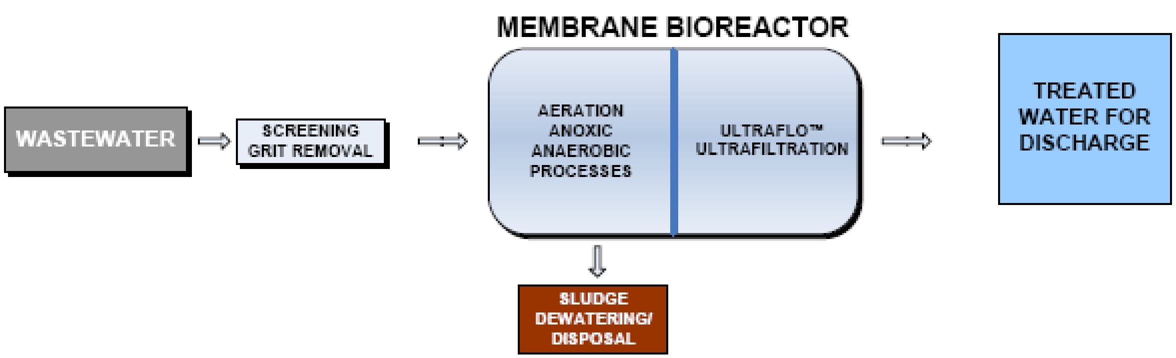
$VSS_{effluent}$ = 0 mg/L

Source: E. Morgenroth,UIUC

(representative values)

MBR for Advanced WWT





- Particle-free effluent
- Absolute barrier for retention of biomass
- Decoupling of HRT and SRT
- Remote-monitoring and control appropriate

But…

Energy + maintenance

Comparison between CAS and MBR space and process requirement (adapted from Ultra-Flo,2007)

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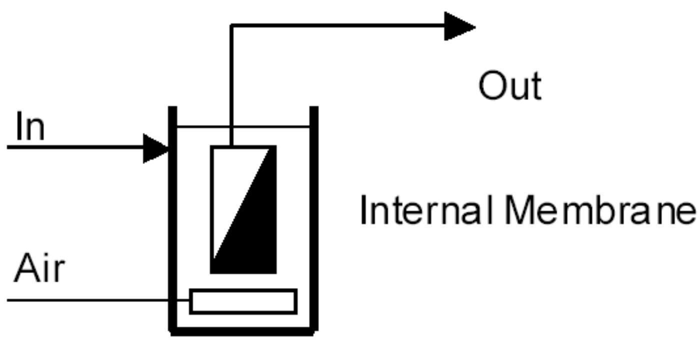
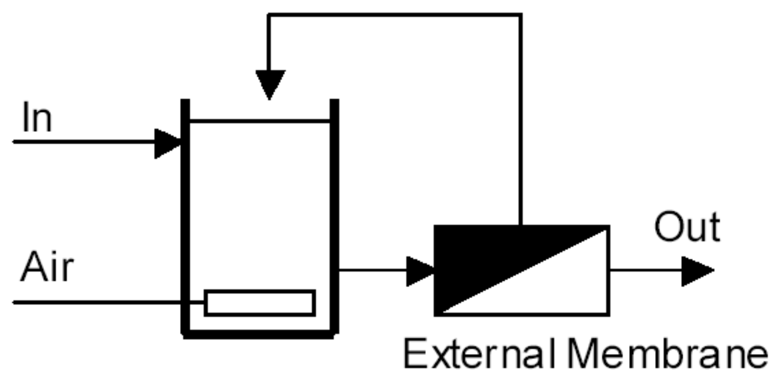
MBR Configurations

- Internal (Submerged)
  - Directly in aeration tank
  - or, in separate filtration tank (for scouring)
  - HF (cassette, bundled), flat sheet, ceramic
  - Less pressure requirement

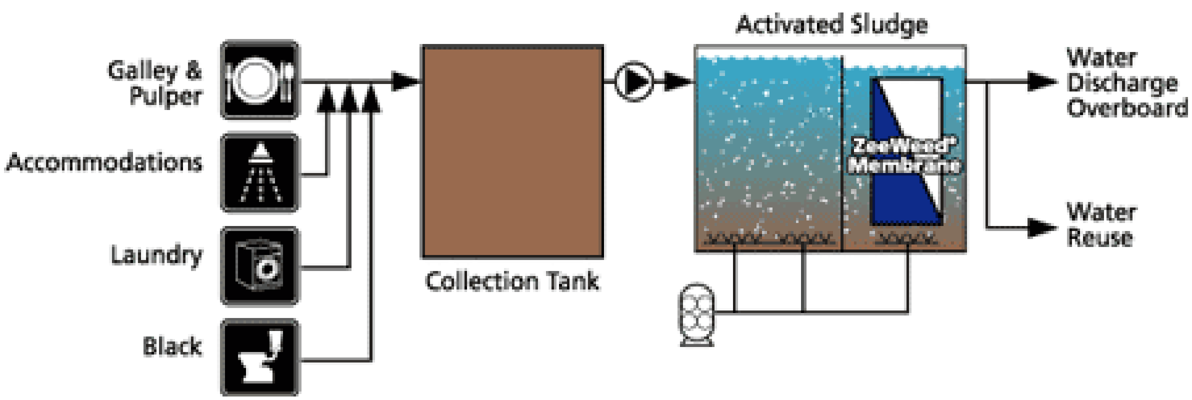
- External (Sidestream)
  - Better control and easier retrofit
  - However, requires greater crossflow and pressure ➔ Greater energy requirement
  - Issue: shear of flocs
  - Tubular (polymer, ceramic), HF (bundled), flat sheet





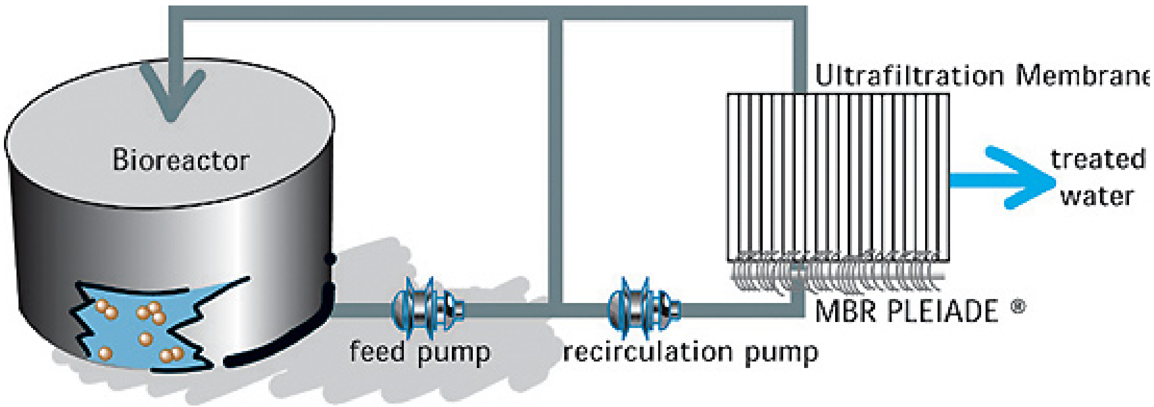
Commercial Application of MBRs for WWT

- **Small systems**
  - Package plants, seasonal WWT
  - Green buildings →
  - Shipboard (cruise ships, warships



Helena Apt. Bldg, NYC (50,000 GPD blackwater to cooling water and irrigation)

MBR on cruise ships



Source: http://www.ship-technology.com/contractors/separators/rhodia/rhodia1.html

Rhodia Orelis

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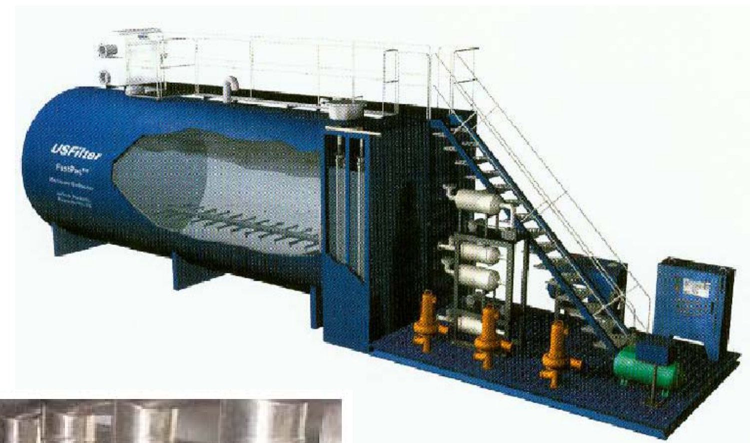
Decentralized WWT and water reuse

- Automated satellite package plants for water reuse
  - Locate along sewer system close to reuse customer (e.g., for irrigation and landscaping)
  - Concept of “sewer mining”
  - ex. *MBR Express*^{TM}
  - ex. FL, WA, CA, GA



FastPac™ MBR System installed in Valley Center, CA

Membrane Module Assembly

Membrane Module Cutaway

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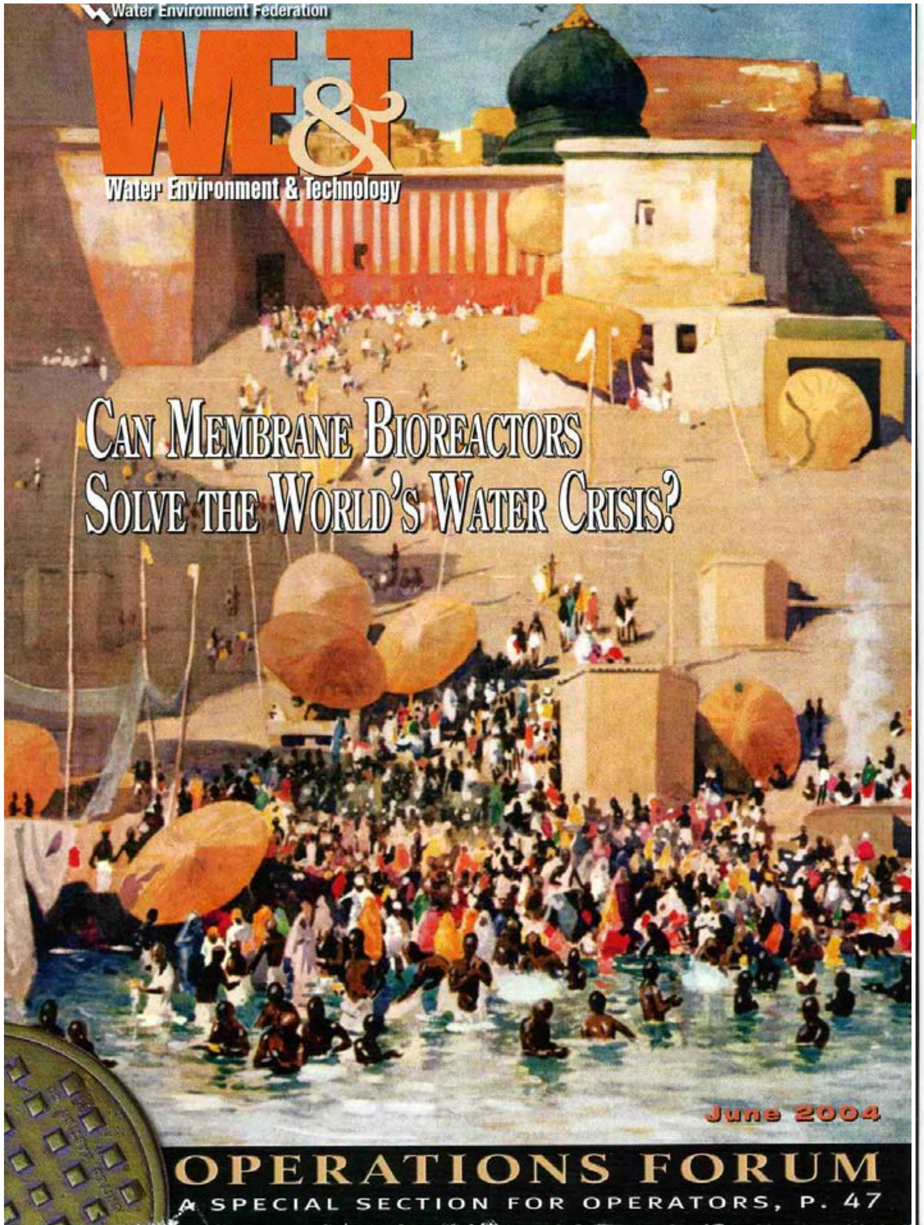
Photos courtesy Siemens (formerly US Filter)



SAFE WATER FOR EVERYONE

Experts suggest that membrane bioreactors may be a key to global water sustainability

Francis A. DiGiano, Gianni Andreottola, Samer Adham, Chris Buckley, Peter Cornel, Glen T. Daigger, A G (Tony) Fane, Noah Galil, Joseph G. Jacangelo, Alfieri Pollice, Bruce E. Rittmann, Alberto Rozzi, Tom Stephenson, and Zaini Ujang

Reuse and decentralization will be essential for meeting human needs for water and sanitation in both developing and developed countries. Membrane bioreactors (MBRs) will be an essential part of advancing such water sustainability, because they encourage water reuse and open up opportunities for decentralized treatment.

These were the conclusions of a Rockefeller Foundation-sponsored Team Residency held at the Bellagio (Italy) Study and Conference Center on April 23–26, 2003. The foundation invited 14 experts on membrane technology, water treatment technologies, and water sustainability from the United States, United Kingdom, Germany, Italy, Australia, Israel, South Africa, and Malaysia to explore the role of MBRs and other membrane processes in achieving sustainable water and sanitation. (The foundation periodically brings together up to 14 participants from developed and developing countries to discuss topics of global importance. The format permits structured and unstructured time to explore common ground and forge shared solutions to tough challenges.)

Membrane Bioreactors Come of Age

MBRs combine activated sludge with membrane filtration (see Figure 1, p. 32). So, in addition to removing biodegradable organics, suspended solids, and inorganic nutrients (such as nitrogen and phosphorus), MBRs retain particulate and slow-growing organisms (thereby treating more slowly biodegraded organics) and remove a very high percentage of pathogens (thereby reducing chemical disinfection requirements). They also require less space than traditional activated sludge systems because less hydraulic residence time (HRT) is needed to achieve a given solids retention time (SRT). In addition, MBRs are more automated, making them ideal for decentralized treatment because they are simpler to operate.

We base the readiness of MBR technology on the following reasons:

- **The engineering principles underlying MBRs are familiar enough to ensure reliability.** Because MBRs combine two familiar technologies — activated sludge and membrane filtration — significant engineering expertise can be applied to MBR design and operation. Several stud-

D. Yen

Potential for great impact…with room for improvement

Sustainability Criteria for MBR Technology

(Balkema *et al.*, 2002 and indicates the Team's ratings for MBRs)

Criteria	Indicators	Improvement needed	Good now
Economic	Cost and affordability	X	
Environmental	Effluent water quality		
	Microbes		X
	Suspended solids		X
	Biodegradable organics		X
	Nutrient removal		X
	Chemicals usage	X	
	Energy	X	
	Land usage		X
Technical	Reliability		X
	Ease of use	X	
	Flexible and adaptable		X
	Small-scale systems		X
Socio-Cultural	Institutional requirements	X	
	Acceptance	X	
	Expertise	X	

OVERALL SUSTAINABILTY GOOD

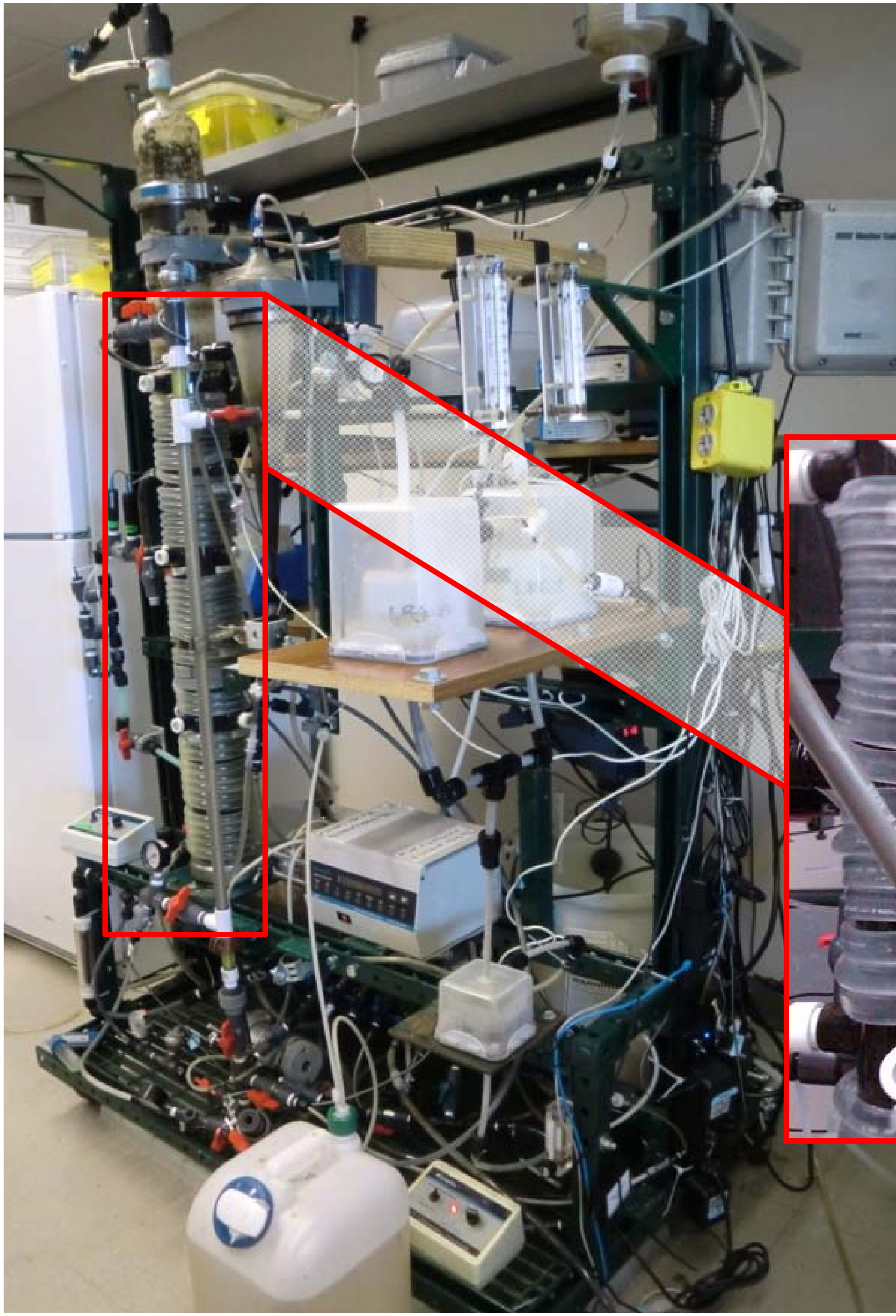
From the **Bellagio Framework 2004**, where, at the invitation of the Rockefeller Foundation, 14 w/ww experts from around the world met in Italy to evaluate MBR technology.

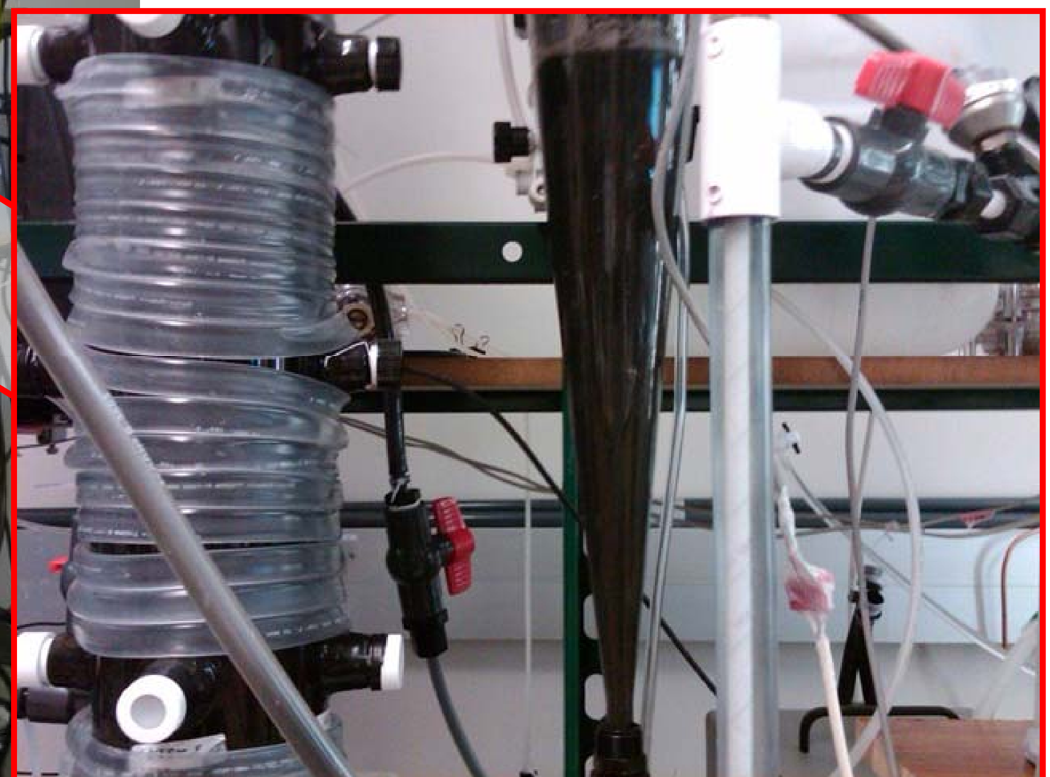
Wat. Environ. Technol. June 2004

Our vision and goals

- Develop an **<u>anaerobic</u> membrane bioreactor (AnMBR)** system, suitable for developing communities, that provides a **high level of treatment and safe recovery of resources** (energy, nutrients and water).
- The AnMBR (***NEWgenerator***^{TM}) will be durable, robust, safe, simple to operate and maintain, low energy, low cost, adaptable to different settings (plug-and-play).
- The ***NEWgenerator***^{TM} will provide flexibility in the reuse of recovered resources based on customer needs.

The anaerobic MBR (AnMBR) at Univ. South Florida





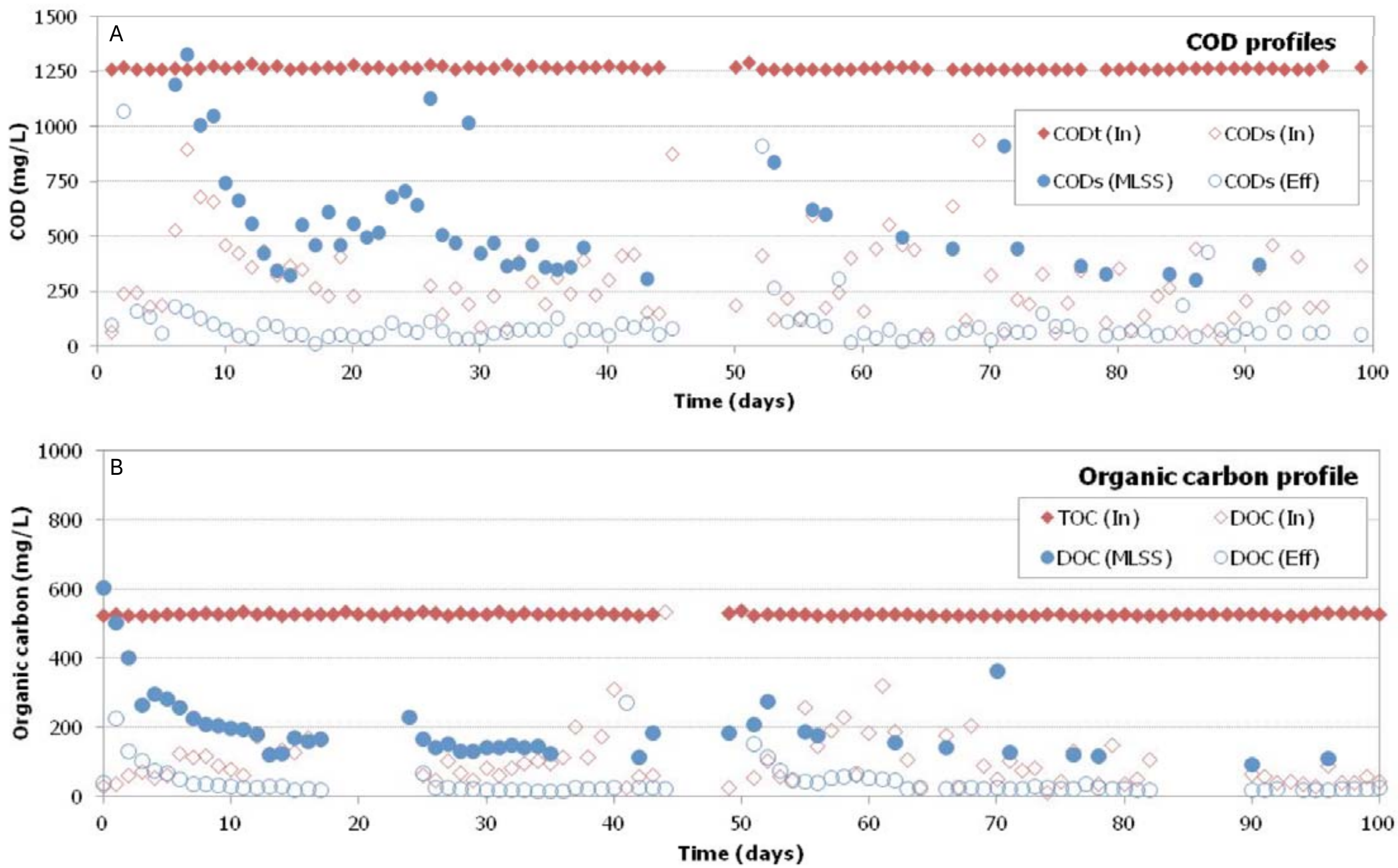
USF

AD + UF membrane

Carbon conversion (to methane)

98% COD conversion

95% TOC conversion



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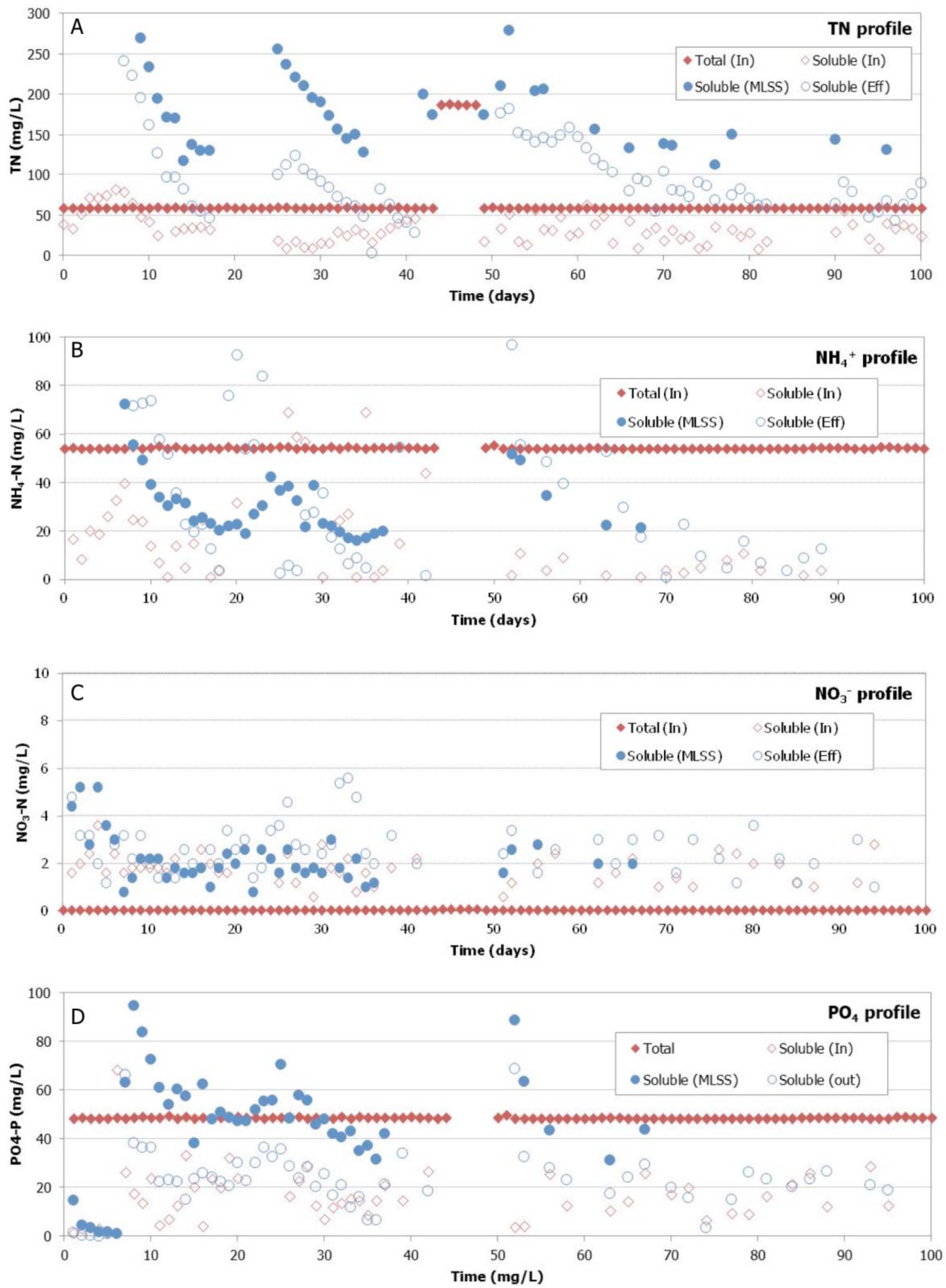
Prieto et al, 2012

N, P conversion



Conversion of organically-bound N, P and released as inorganic N, P

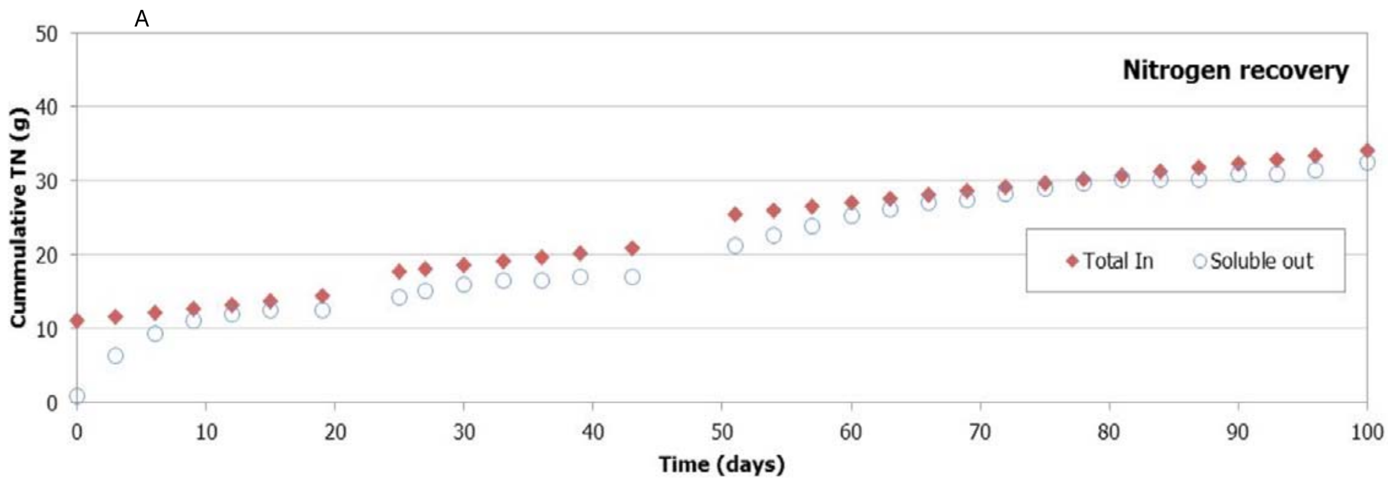
(+ initial release of residual filtrate from digester sludge)

Prieto et al, 2012

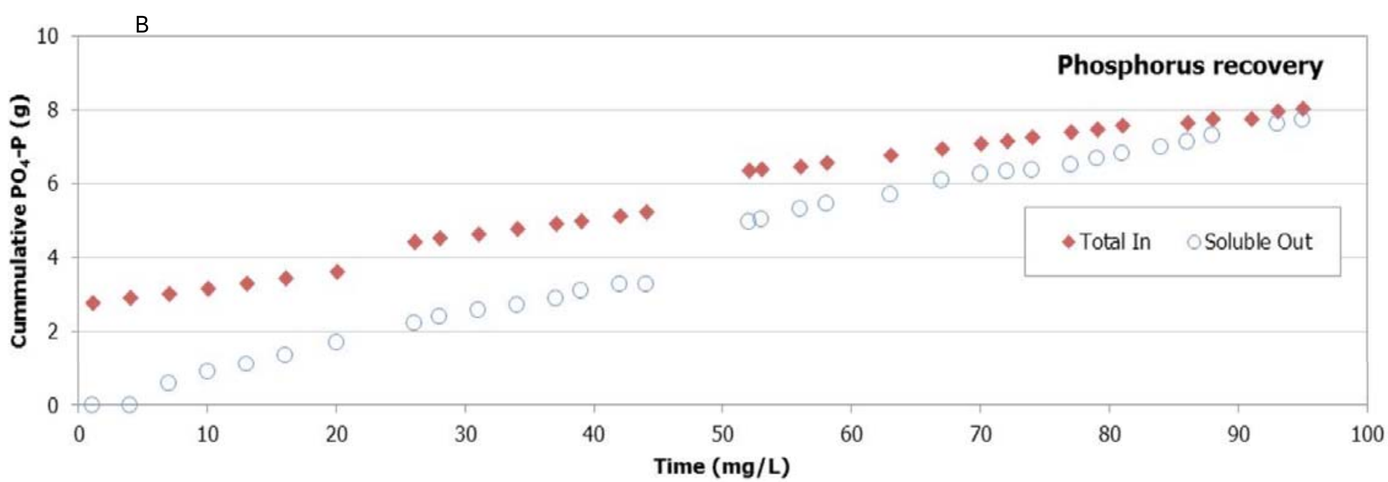
USF D. Yeh

N, P recovery for reuse (fertigation)

95% N recovered (cumulative)



93% P recovered (cumulative)



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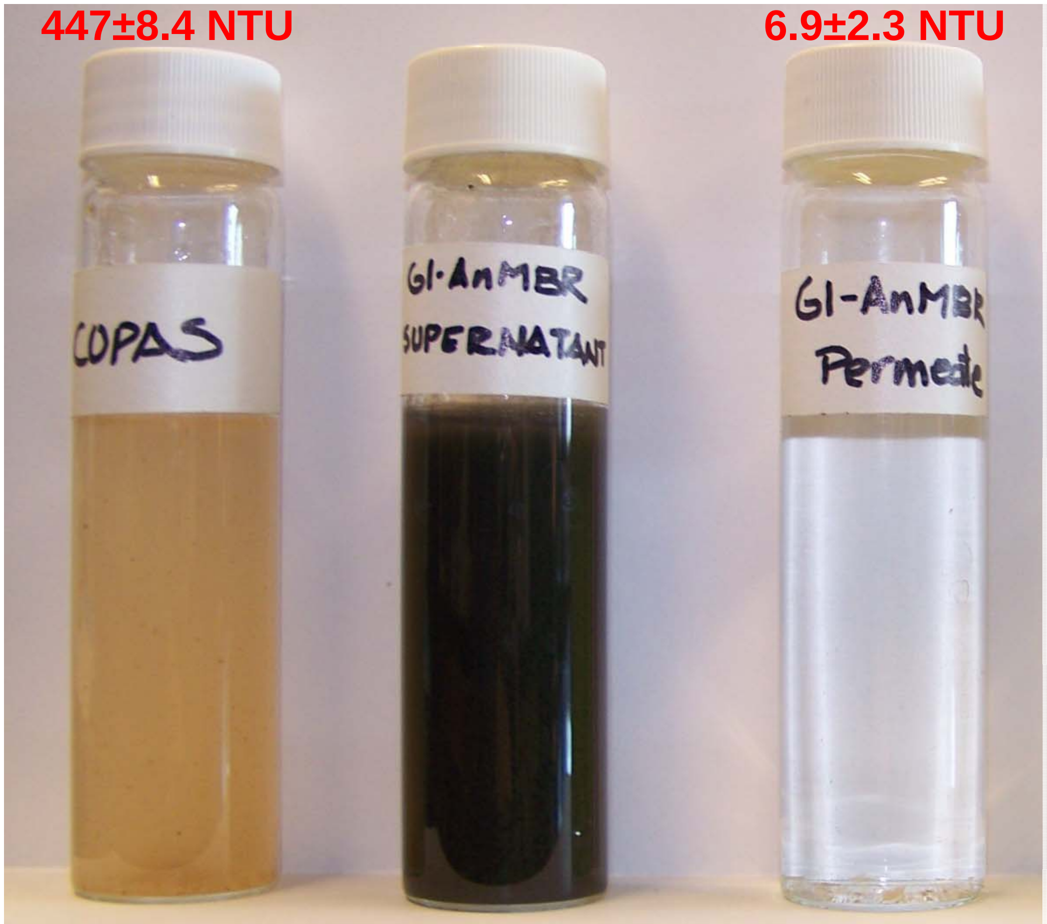
Prieto et al, 2012

AnMBR summary

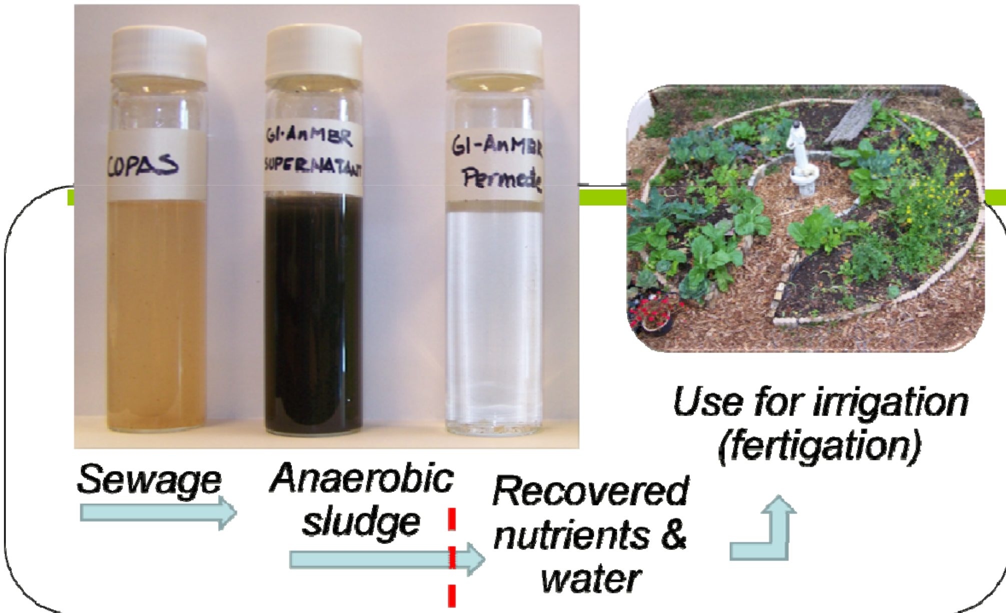
Turbidity 447±8.4 NTU

Turbidity 6.9±2.3 NTU

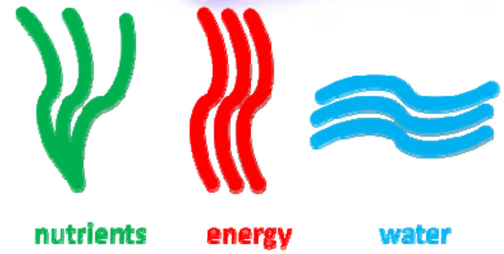


- Filtration sustained at a flux of 10-15 LMH.
- Removal efficiencies of organic matter (i.e. up to 98% and 95% in COD and TOC removal respectively)
- Biogas production (4.5 L/d)
- Recovery of soluble fertilizers from sewage (95% N and 93% P)
- The energy footprint of this configuration ranged from -1.2 to 0.7 kWh/m^3 and -2.3 to -0.5 kWh/m^3, for lab-scale and full-scale systems, respectively

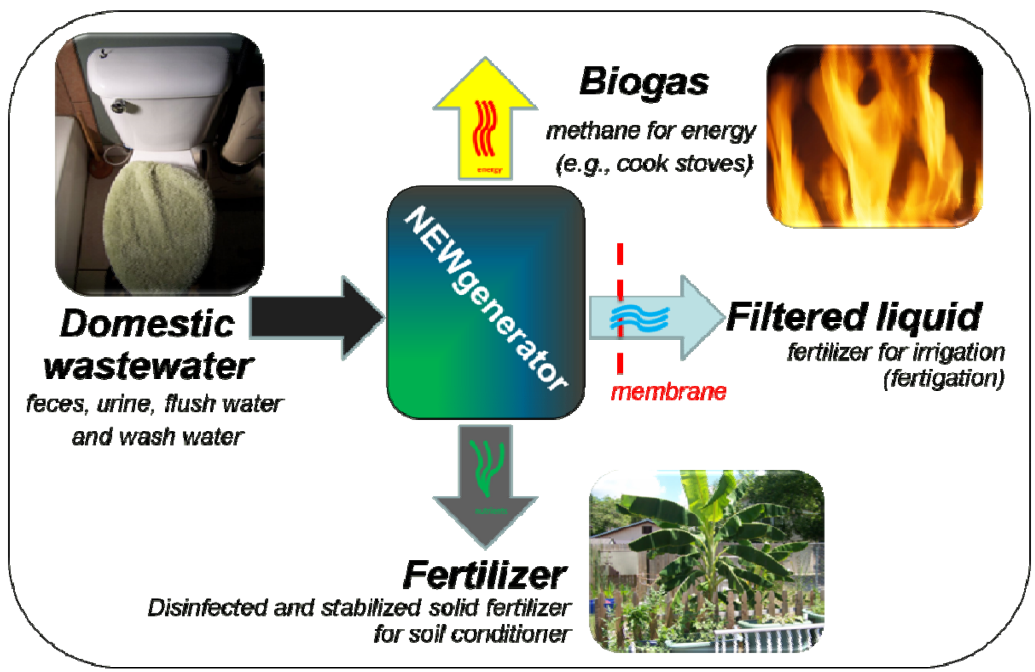
Sanitation



NEWgenerator TM



Creating Value Added Products



BILL & MELINDA GATES foundation

Potential to contribute on:

Sanitation	Water
Energy	Food
Health	Gender
Economics	Empowerment

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Recovery of nutrients

- Nitrogen, phosphorus, potassium

- Struvite and other precipitates
- Biosolids
  - Bio-P phosphorus recovery

- Crop growth

- Algae biofuel

- Liquid fertilizer

Algae biofuel

From Cormier 2010

Synergy of Algae and Wastewater

http://www.waterencyclopedia.com/images/wsci_04_img0570.jpg

Requires O_2

Produces CO_2

Contains Nutrients

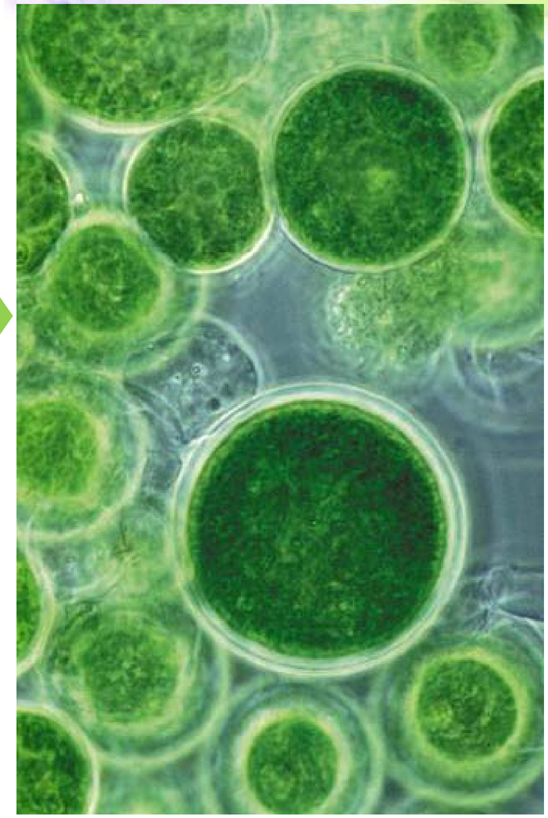
Requires Energy

Produces O_2

Requires CO_2

Requires Nutrients

Harnesses Energy



http://saferenvironment.files.wordpress.com/2008/10/alge.jpg

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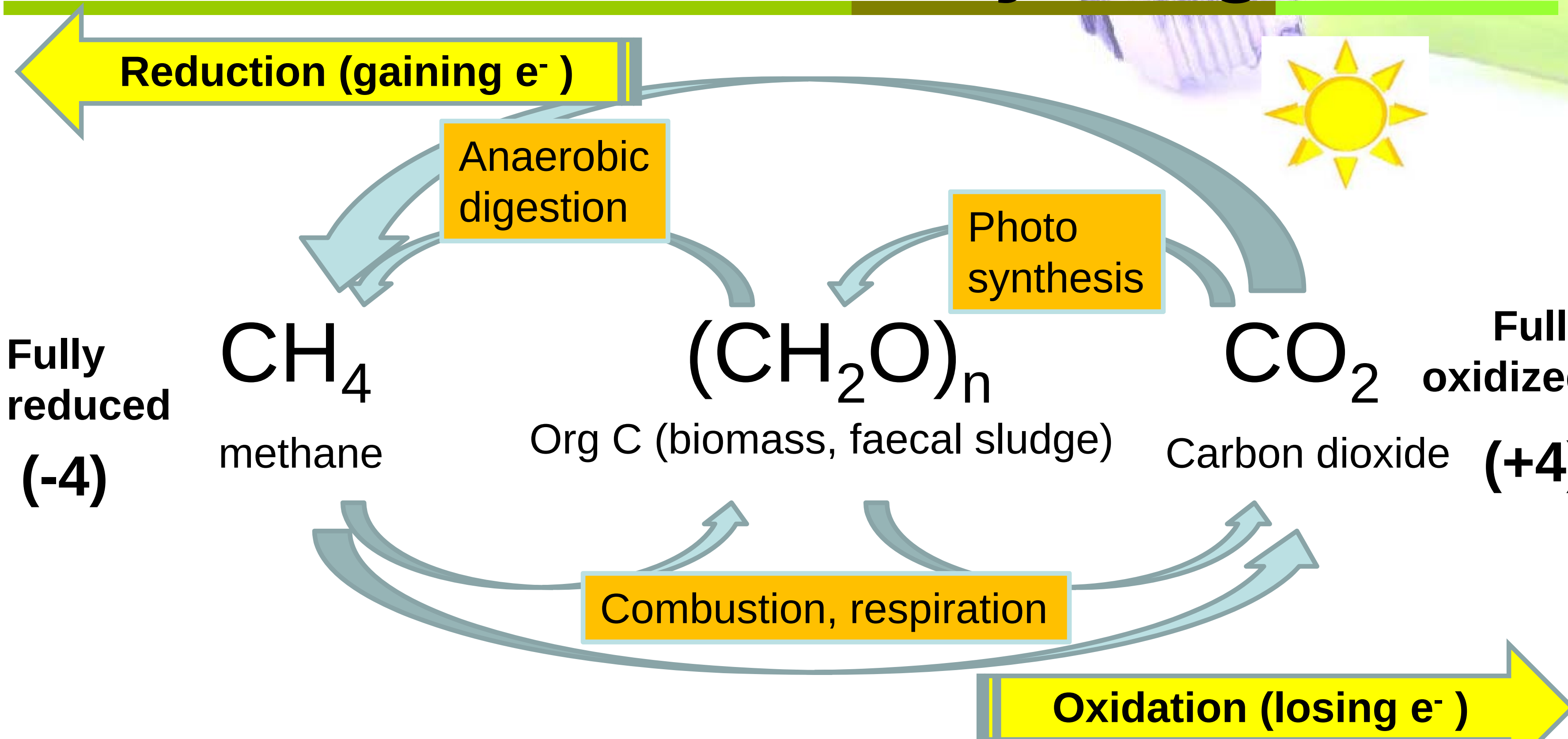
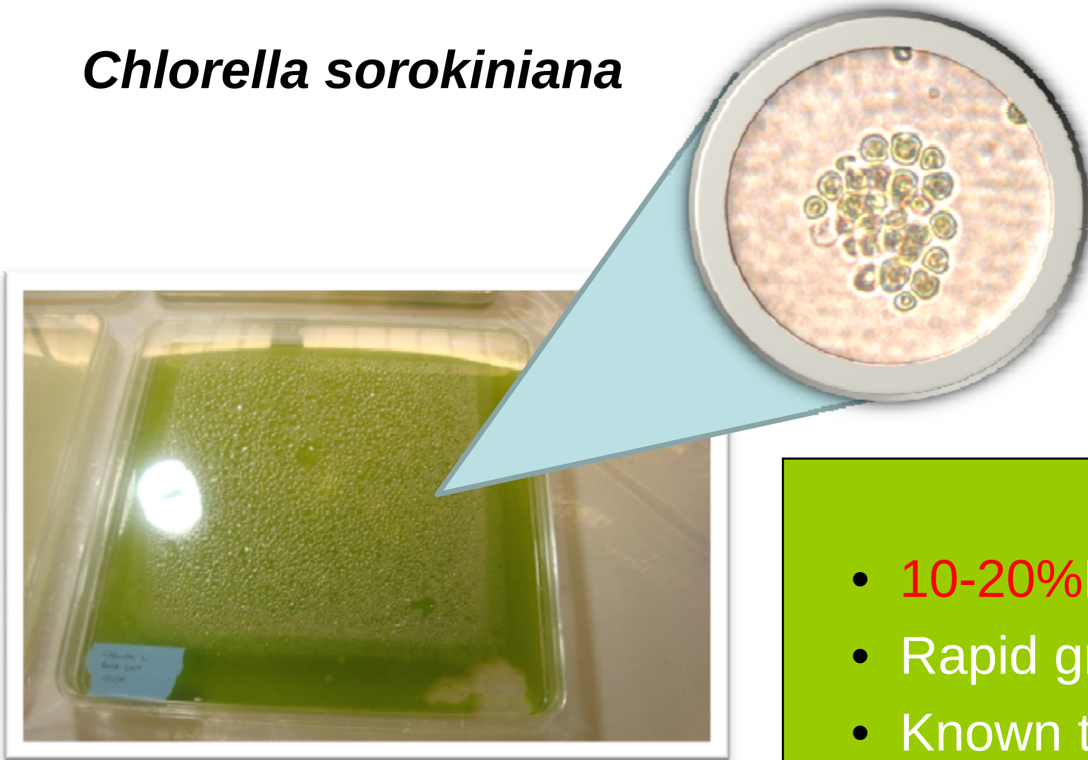
Energy states of carbon all about **biorecycling**



	Methane	biomass	Carbon dioxide
Energy	rich	moderate	none
Redox state	-4	In between	+4
COD (energy)	4 g OD/g (180.4 Wh /g)	Typically 1-3 g OD/g	zero

The Right Algae for the Job

Chlorella sorokiniana



- 10-20%Lipid content by dry weight
- Rapid growth rates
- Known to grow in WW with high Nutrient content
- Can withstand high UV bombardment
- Has high protein content
- Can use NH_4^+

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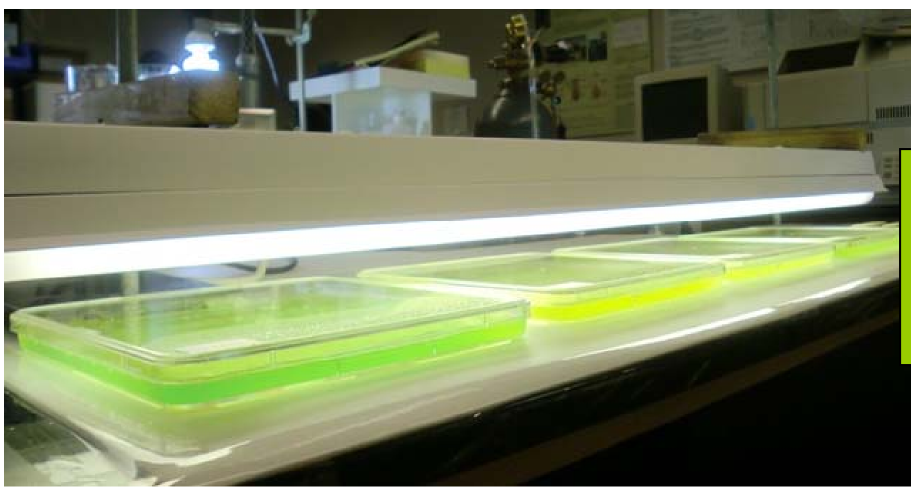
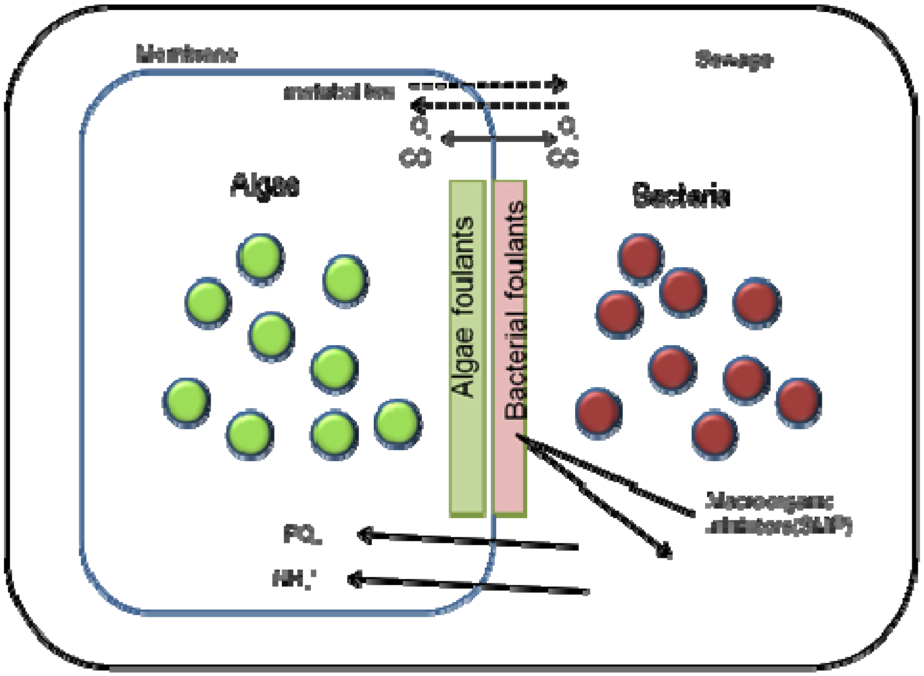
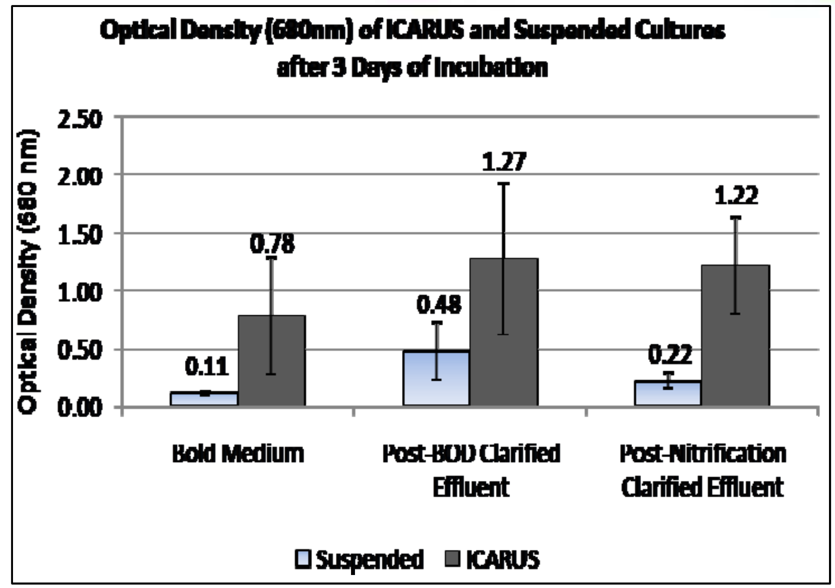
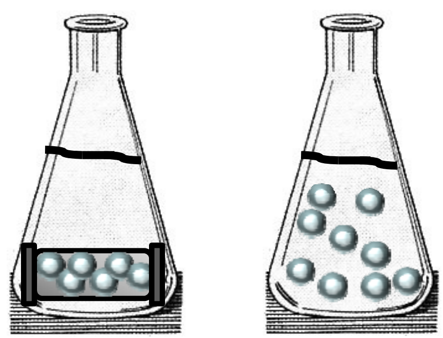
From batch to photobioreactor



Isolated Cultivation of Algal Resources from Sewage (ICARUS)







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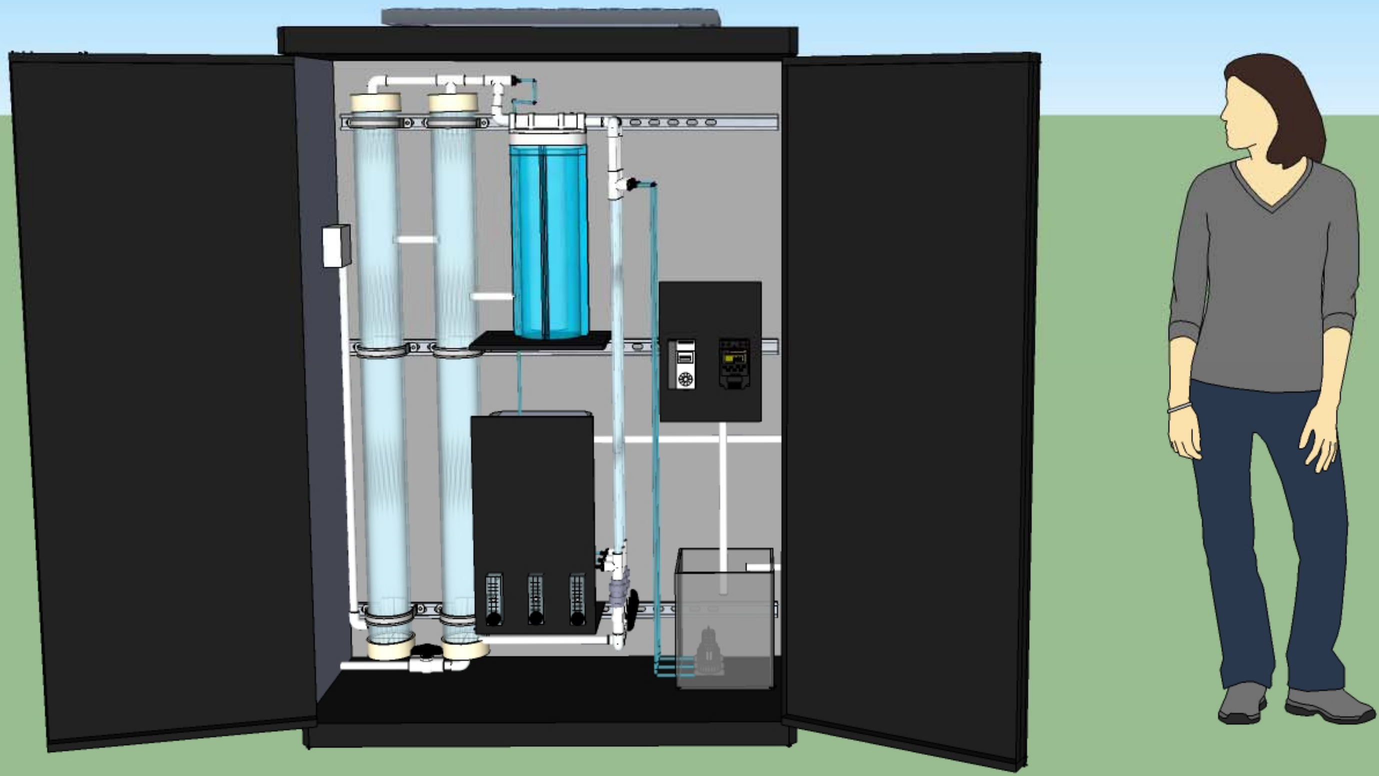
NEWgenerator™

Resource recovery machine in a box

NEWgenerator^{TM}

Resource recovery machine in a box



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Partnerships

- Integration of **research**, **education** and **practice**
- Training of graduate and undergraduate students
- Partnership with local K-6 green school in Florida (**Learning Gate Community School**)
- Field testing *NEWgenerator*^{TM} pilot using the wastes from the school's septic tank
- Additional partners in science centers, museums, and WW utilities.
- Established the **BioRecycling/BioEnergy Research and Training Station (BBRATS)**, confluence of three projects:
  - Global sanitation (Gates Foundation)
  - Algae biofuel (National Science Foundation)
  - Food waste mgmt (Univ. South Florida Graduate School)

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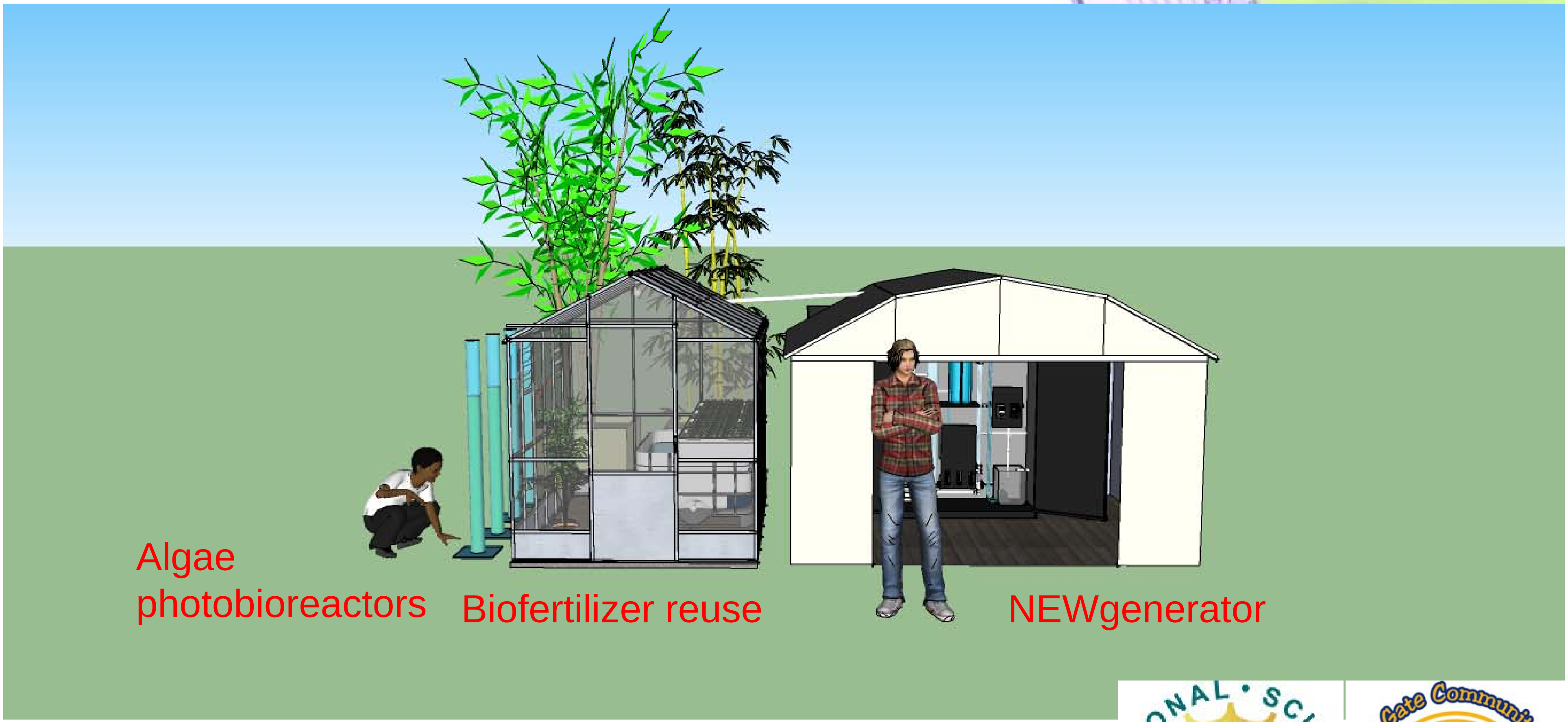
Learning Gate Community School
Nature Is Our Best Teacher


USF
BULLS

BioRecycling/BioEnergy Research and Training Station (BBRATS)



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USF UNIVERSITY OF SOUTH FLORIDA BILL & MELINDA GATES foundation NATIONAL SCIENCE FOUNDATION NSF Learning Gate Community School Nature Is Our Best Teacher

BioRecycling/BioEnergy Research and Training Station (BBRATS)

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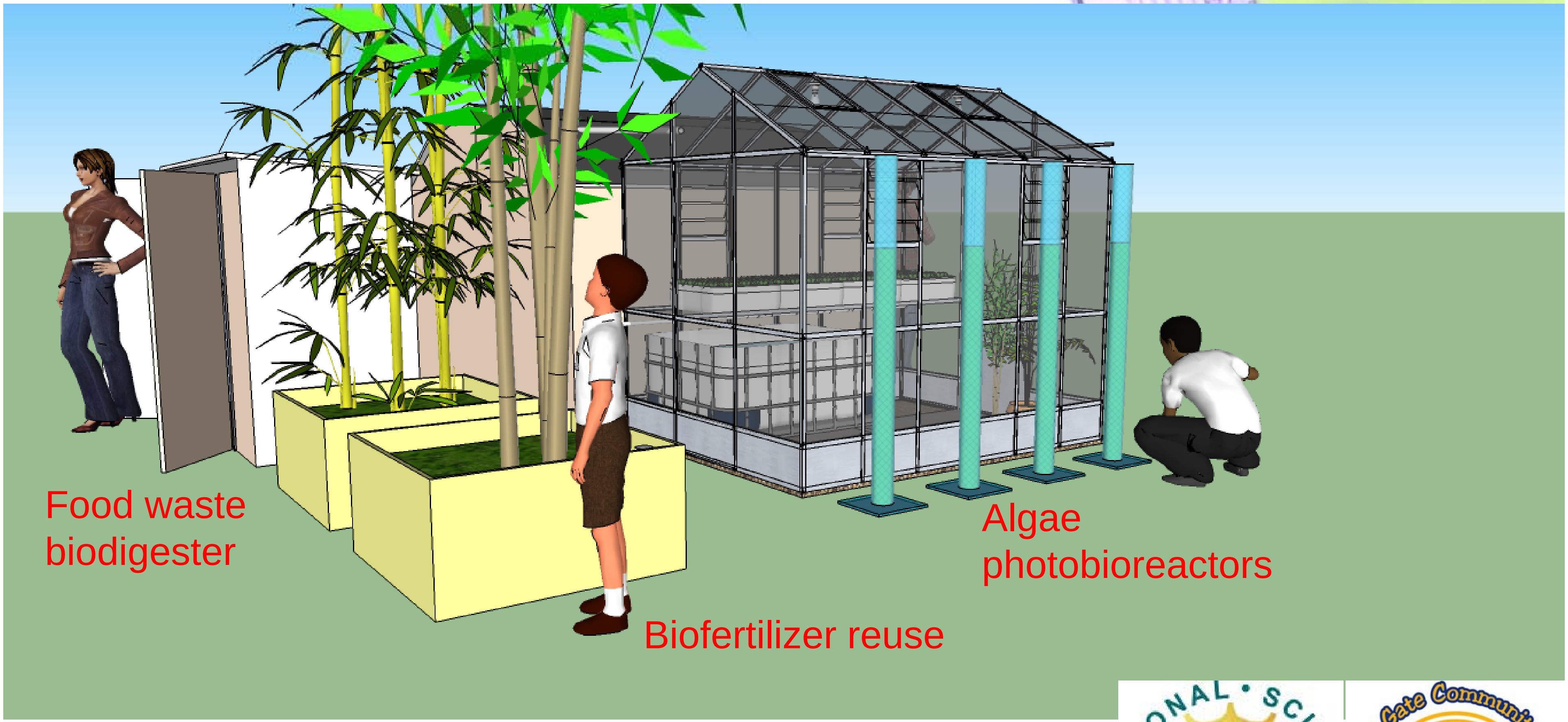
BioRecycling/BioEnergy Research and Training Station (BBRATS)



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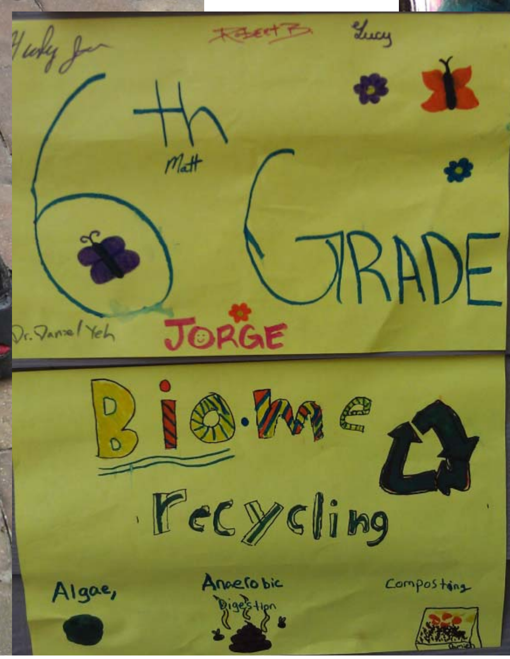
Education

- Integrating BBRATS into curriculum.
  - Hands-on B/B modules on **AD, algae, composting.**
  - Capacity building, systems thinking
- In Nature, there is no such thing as waste. Everything is a souce of food and energy.
- There is no waste problem, only a carbon and nutrient mismanagement problem

Learning about AD…

LANCO



Robert B
Lucy
6th
Matt
GRADE
Dr. Daniel Yeh
JORGE
Bio·me
recycling
Algae,
Anaerobic Digestion
Composting

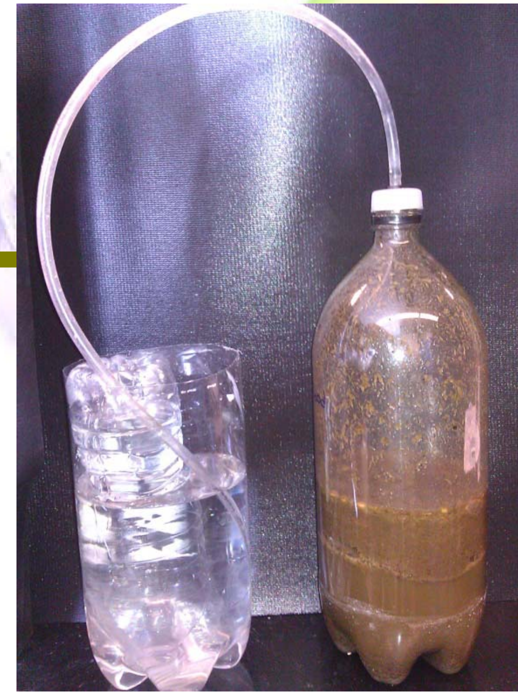
Coca-Cola
Sharpie
Nerds

We built our own anaerobic digesters…


DO NOT TOUCH
Coca-Cola
Diet Coke
Sprite


Diet Coke
Coca-Cola

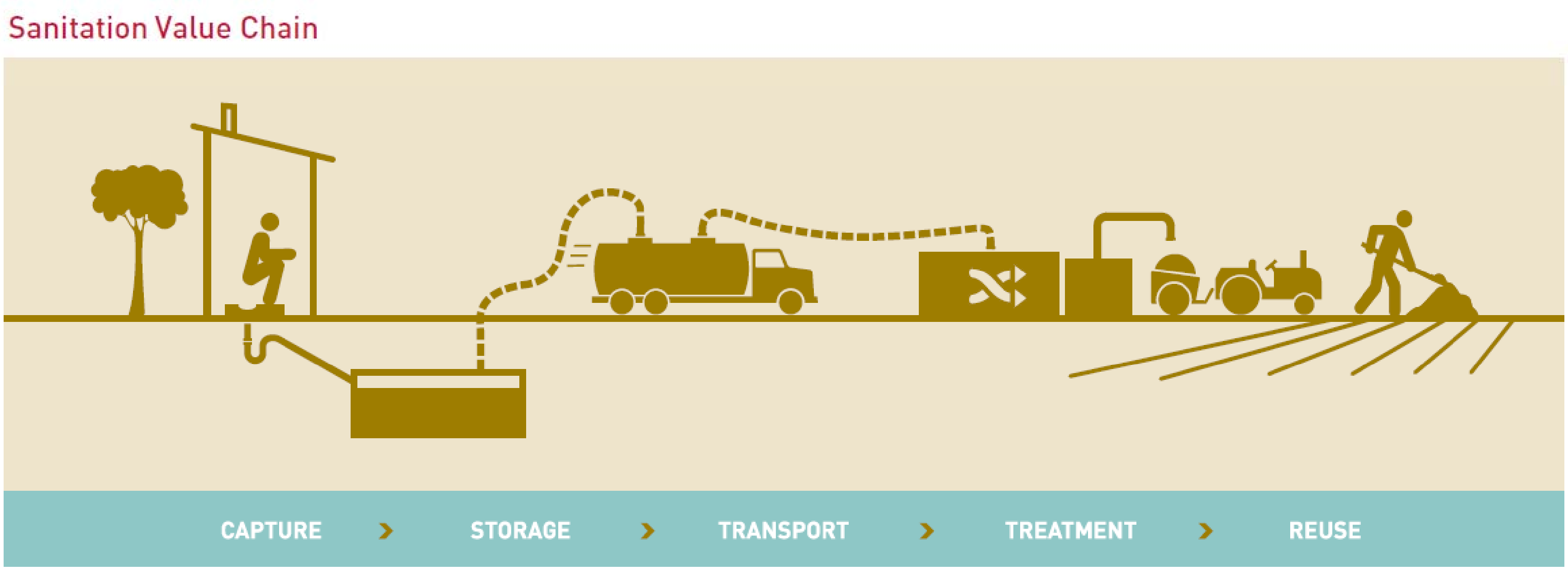

BookHolders.com
Miracle-Gro
Seed Starting Potting Mix
FAST ROOT DEVELOPMENT
TOP GUN



BioRecycling Education Module (6th grade class)

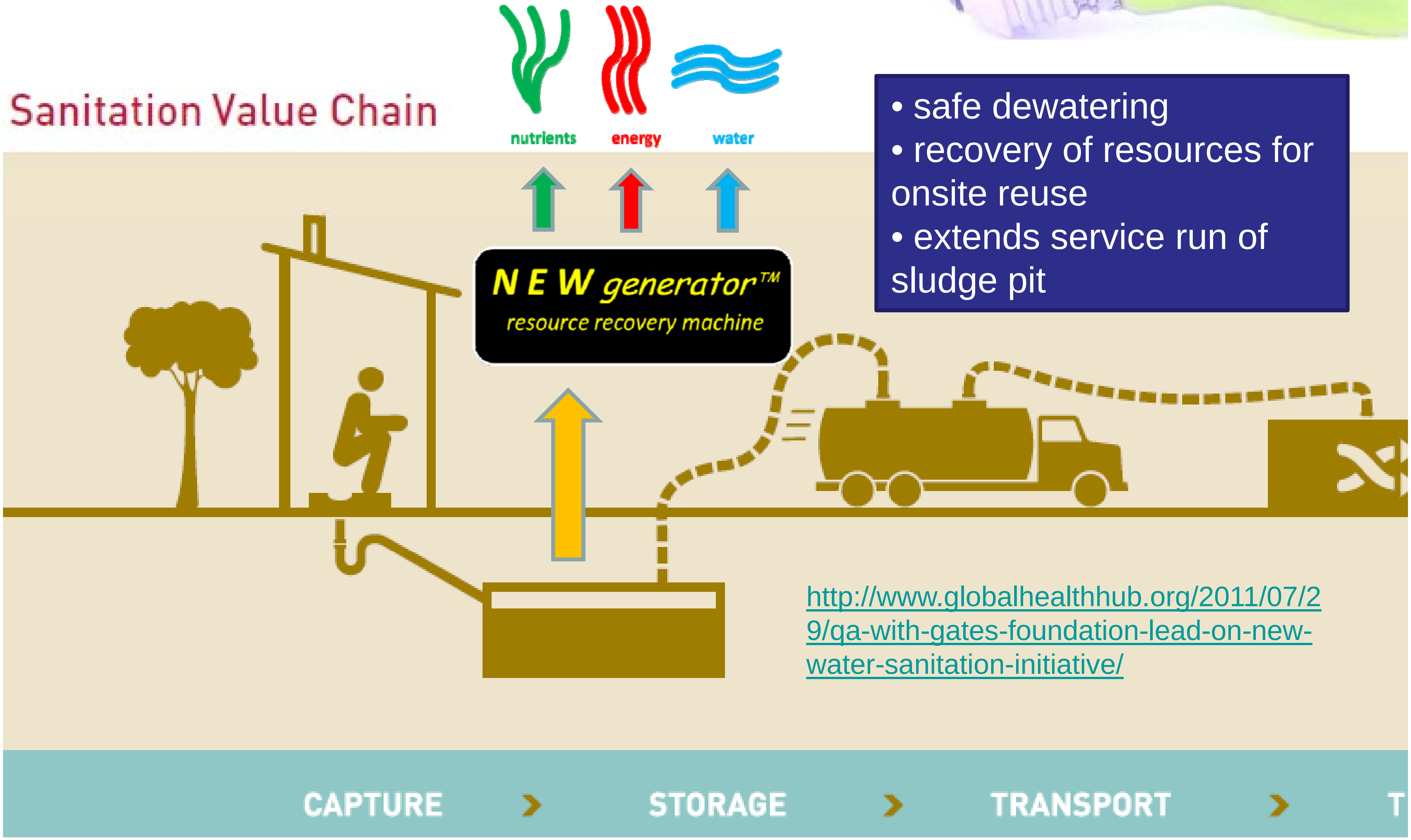
Sanitation Value Chain

- Per Dr. Doulaye Kone (Gates Foundation)



http://www.globalhealthhub.org/2011/07/29/qa-with-gates-foundation-lead-on-new-water-sanitation-initiative/

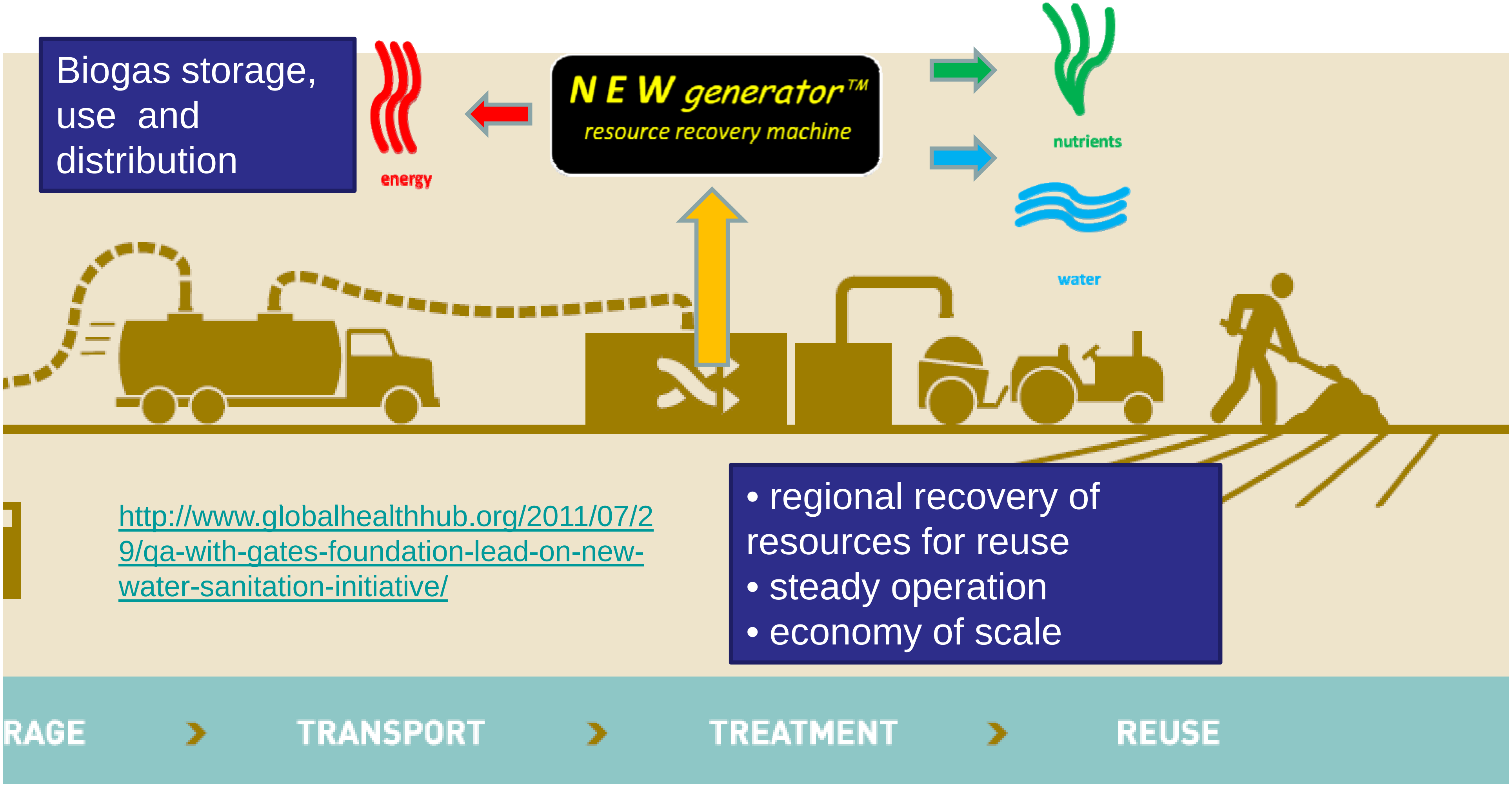
Small-scale *NEWgenerator*™ for **onsite** resource recovery and reuse



- safe dewatering
- recovery of resources for onsite reuse
- extends service run of sludge pit

http://www.globalhealthhub.org/2011/07/29/qa-with-gates-foundation-lead-on-new-water-sanitation-initiative/

Larger-scale *NEWgenerator*™ for **regional** resource recovery and reuse



http://www.globalhealthhub.org/2011/07/29/qa-with-gates-foundation-lead-on-new-water-sanitation-initiative/

- regional recovery of resources for reuse
- steady operation
- economy of scale

Looking ahead…

Looking for technology partners to complement *NEWgenerator*^{TM} and create synergy

Looking for implementation partners to field test

Let's talk!

Waste Bioreactor Recovered Resource

Oct 2011 - Toilet mfgr TOTO announces toilet-powered vehicle to trek across Japan

…perhaps in a not-too-distant future?

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Twitter @dhyeh
http://NEWgenerator.tumblr.com

USF Membrane Biotechnology Lab
http://mbr.eng.usf.edu/

Graphics: Ana Lucia Prieto

Thank you for your attention. Questions?

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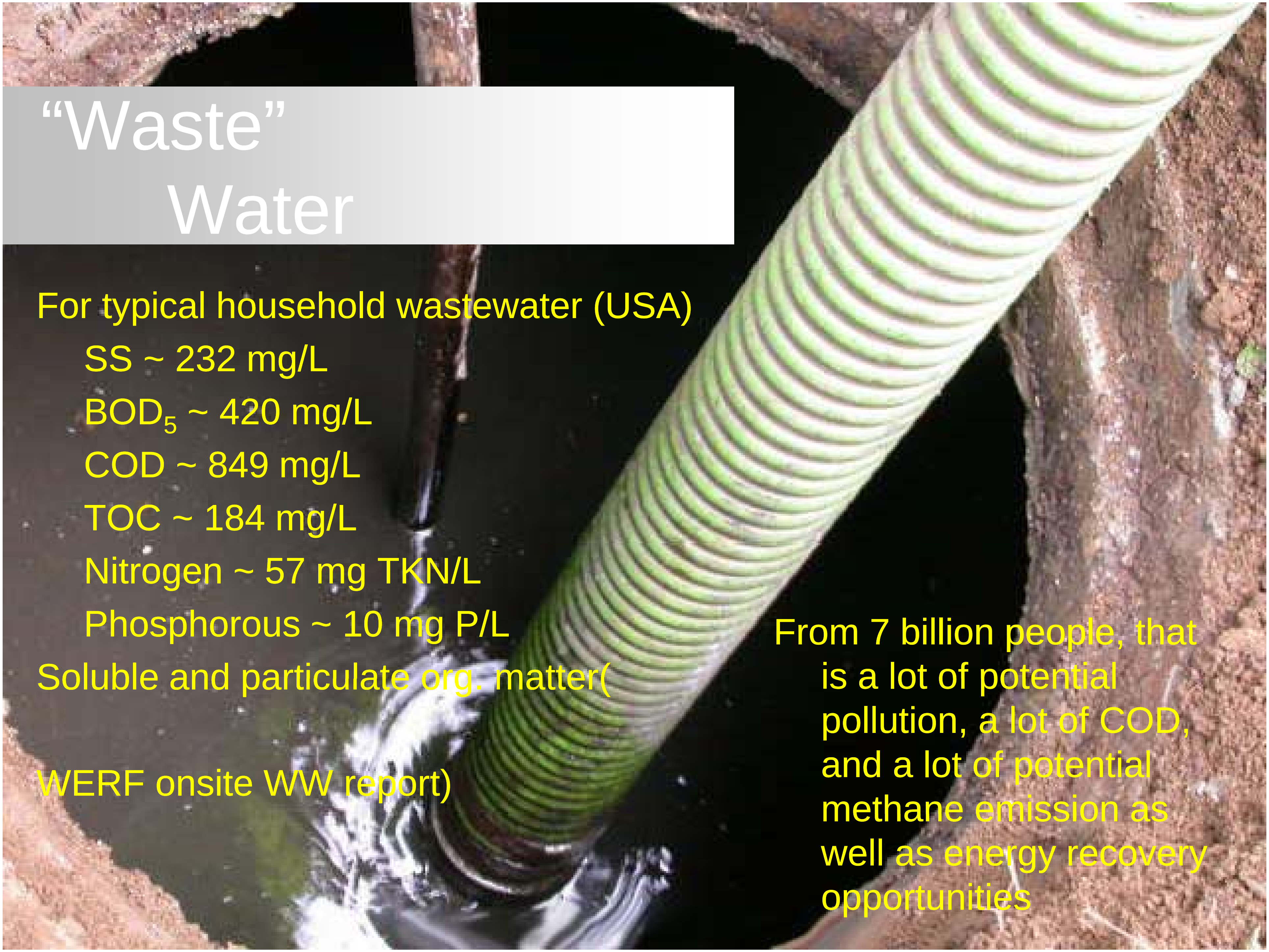
USF Membrane Biotechnology Lab
http://mbr.eng.usf.edu/

FOX 13 video

- http://www.myfoxtampabay.com/story/18612577/could-a-new-energy-source-start-right-here



"Waste" Water

For typical household wastewater (USA)

- SS ~ 232 mg/L
- BOD_5 ~ 420 mg/L
- COD ~ 849 mg/L
- TOC ~ 184 mg/L
- Nitrogen ~ 57 mg TKN/L
- Phosphorous ~ 10 mg P/L

Soluble and particulate org. matter(

WERF onsite WW report)

From 7 billion people, that is a lot of potential pollution, a lot of COD, and a lot of potential methane emission as well as energy recovery opportunities

Constituents in household sewage

		Median	This Study Range[1]	Lit. Review	U.S. EPA (2002)	Crites and Tchobanoglous (1998)
Alkalinity (as $CaCO_3$)	Raw	260	65-575	NR	NR	NR
	STE	411	172-862	NR	NR	60-20
TS	Raw	1,028	252-3,320	NR	500-880	350-1,200
	STE	623	290-3,665	NR	NR	NR
TSS	Raw	232	22-1,690	18-2,230	155-330	100-350
	STE	61	28-192	22-276	50-100	40-140
cBOD5	Raw	420	112-1,101	30-1,147	155-286	110-400
	STE	216	44-833	38-861	140-200	150-250
COD	Raw	849	139-4,584	540-2,404	500-660	250-1,000
	STE	389	201-944	157-1,931	NR	250-500
TOC	Raw	184	35-738	NR	NR	80-290
	STE	105	50-243	NR	31-68	NR
DOC	Raw	110	29-679	NR	NR	NR
	STE	66	22-140	NR	NR	NR
Total nitrogen	Raw	60	9-240	44-189	26-75	20-85
	STE	63	27-119	26-24	40-100	NR
TKN (as N)	Raw	57	16-248	43-124	NR	NR
	STE	60	33-171	27-94	19-53	50-90
Ammonium-nitrogen (as N)	Raw	14	2-94	9-154	4-13	12-50
	STE	53	25-112	0-96	NR	30-50
Nitrate-nitrogen (as N)	Raw	1.9	BDL-9	0.05-1.1	<1	0
	STE	0.7	BDL-7	0-10.3	0.01-0.16	NR
Total phosphorus	Raw	10.4	0.2-32	13-26	6-12	4-15
	STE	9.8	0.2-33	3-40	7.2-17	12-20

COD represents potential energy!

- What is COD?
  - **Chemical oxygen demand**, or the ability for *reduced (i.e., electron rich) WW organic matter* to donate electrons to an electron-hungry *electron acceptor* (e.g., O_2) and converting it to a reduced form (H_2O)

$$\mathrm{OrgC} \rightarrow CO_2 + e^-$$
$$e^- + O_2 \rightarrow H_2O$$

$$\mathrm{OrgC} + O_2 \rightarrow CO_2 + H_2O$$

  - COD is a measure of the potential energy <u>stored</u> within WW organic matter

Please not that energy can potentially be extracted from the oxidation of any reduced chemical species (e.g., N and S). Reduced N species such as NH_4^+ exert a nitrogenous oxygen demand (NOD) and can also be a significant source of energy (40 mg/L TKN-N x 4.57 mg OD/mg TKN-N = **183 mg OD/L**). However, the focus of this particular presentation is only on energy from organic matter.

How much energy can we potentially get from wastewater organic matter?

Maximum potential from COD (assuming no growth)

please note that potential energy from NOD (from reduced N such as NH4+) is not included in this calculation

0.5 g COD/L (typical conc) x 0.25 g CH_4/g COD x 1000L/m^3 (3784 m^3/MG) = **125 g CH_4/m^3 of municipal WW (473 kg CH_4/ MG)**

125 g CH_4/m^3 x 50.1 kJ/g CH_4 x 0.000278 kWh/kJ = **1.74 kWh/m^3 of municipal WW (6.59 MWh/MG)**

Ex. loading: 6.59 MWh/MG x 50 MG/d x d/24hr = **13.7 MW from municipal WW @ 50MGD (max potential)**
(Tampa WWTP)

Compare to Tampa Electric's 2000 MW Big Bend power plant (natural gas)

Comparison: the Barycz landfill in Krakow, Poland generates 1 MW

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Energy consumption for wastewater treatment, example from Iran

Table 3: Average electrical energy consumption in various processes of plant

Process	Average power consumption (kWh) of 1000 m^3 crude sewage
1. Preliminary treatment	12.67
2. Primary sedimentation	0.91
3. Recirculation pumping of activated sludge	34.19
4. Aeration	230.84
5. Digestion tank (Mixing and Pumping)	20.86
6. Final sedimentation	0.68
Total input	300.1458

0.3 kWh/m³ consumed for WWT

Source: Nouri et al 2007 (data from WWTP in Iran)

Can WWT be energy neutral?

- Can WWTP be energy neutral, or even energy surplus to export energy to the grid?

0.3 kWh/m³ consumed for WWT (Nouri et al 2007)

Excess energy for export???

0.44 kWh/m³ potential from waste organic matter (assume harvesting 25% of max potential at 1.74 kWh/m³) *

Example, small (20,000 p.e.) WWTP in Czech Republic generate AD biogas to heat nearby homes

* Assuming 500 mg/L COD in WW