Biotechnology and Energy Conservation

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14^{th} Lecture
Biogas and Biohydrogen

The Aim:

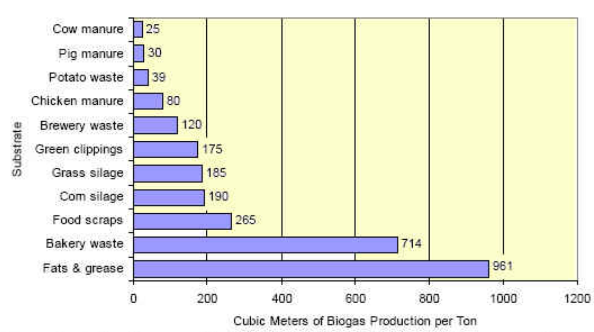
- Students can explain the method of biogas and biohydrogen production
- Students can describe source of raw material and agents (microbes) for producing biogas and biohydrogen

Biogas

- Biogas is gas produced biologically (fermentation under anaerobic microbes) from bio-organic substances.
- Average concentration of substances composition of raw biogas:

Compositions	Concentration
Methane (CH_4)	50-57%
Carbon dioxide (CO_2)	25-45 %-v
Water (H_2O)	2-7 %-v, (20-40°C)
Hydrogen sulfide (H_2S)	20-20,000 ppm
Nitrogen (N_2)	< 2 %-v
Oxygen (O_2)	< 2 %-v
Hydrogen (H_2)	<1 %-v

Influence of substrates type (production level of biogas

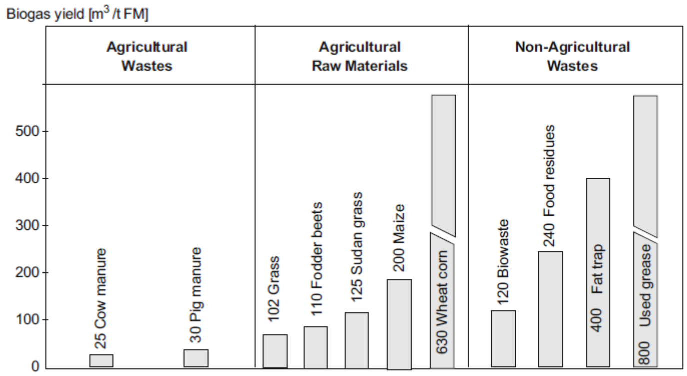


Source: Data derived from www.biogas-energy.com, © 2007 Biogas Energy, Inc., translated from: Basisdaten Biogas Deutschland, Marz 2005,: Fachagentur Nachwachsende Rohstoffe e.V.

Gross crop yield and biogas potential of different crops (Weiland, 2010)

Crop	Crop yield (t FM/ha)	Biogas yield (Nm^3/(t VS)	Methane content (%)
Sugar beet	40–70	730–770	53
Fodder beet	80–120	750–800	53
Maize	40–60	560–650	52
Corn cob mix	10–15	660–680	53
Wheat	30–50	650–700	54
Triticale	28–33	590–620	54
Sorghum	40–80	520–580	55
Grass	22–31	530–600	54
Red clover	17–25	530 -620	56
Sunflower	31–42	420–540	55
Wheat grain	6–10	700–750	53
Rye grain	4–7	560–780	53

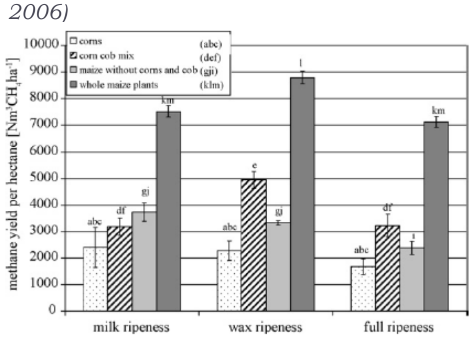
Maximal biogas yield and theoretical methane contents (Baserga, 1998; Weiland, 2010)



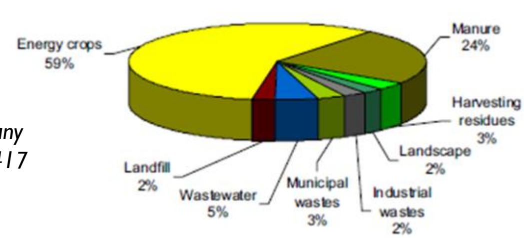
Substrate	Biogas (NM³/t TS)	CH_4 (%)	CO_2 (%)
Carbohydrates*	790-800	50	50
Raw protein	700	70-71	29-30
Raw fat	1,200-1,250	67-68	32-33
Lignin	0	0	0

*) *Only polymers from hexose, not inulin and single hexose*

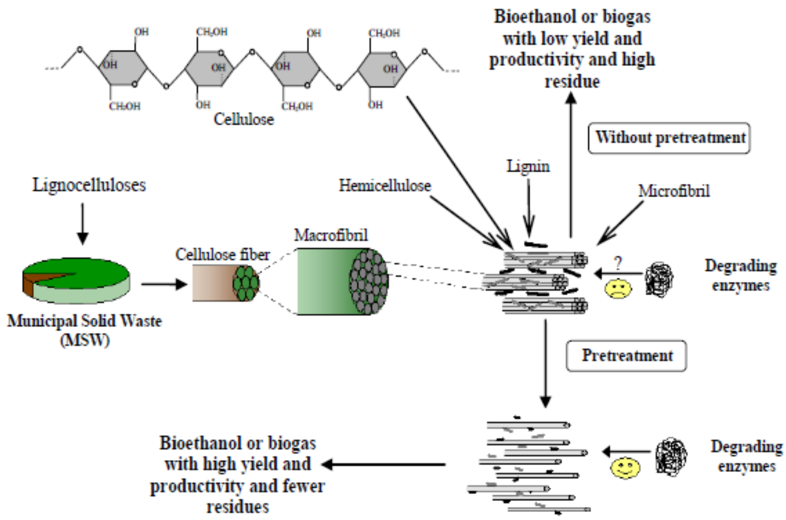
Influence of harvesting technology on biogas production (Amon et al., 2006)



Usable biogas potential in Germany in 2008. Total energy potential : 417 PJ/a (Weiland, 2010)



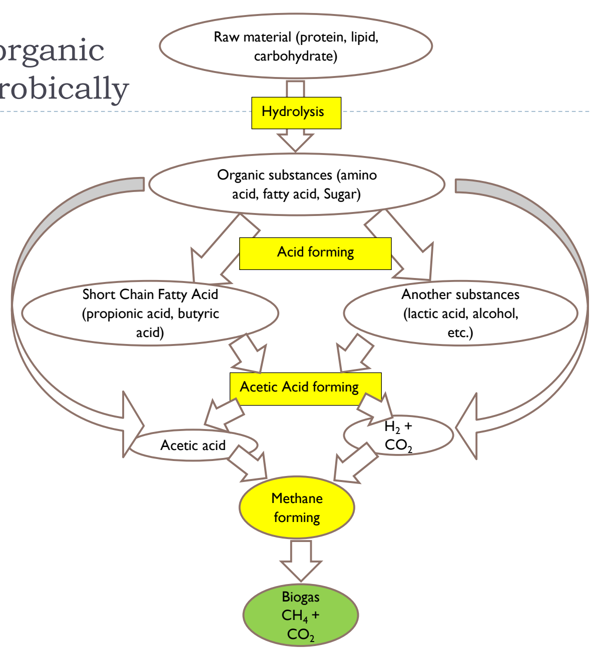
Influence of pre-treatment on bioethanol/biogas production (Taherzadeh and Karimi, 2008)



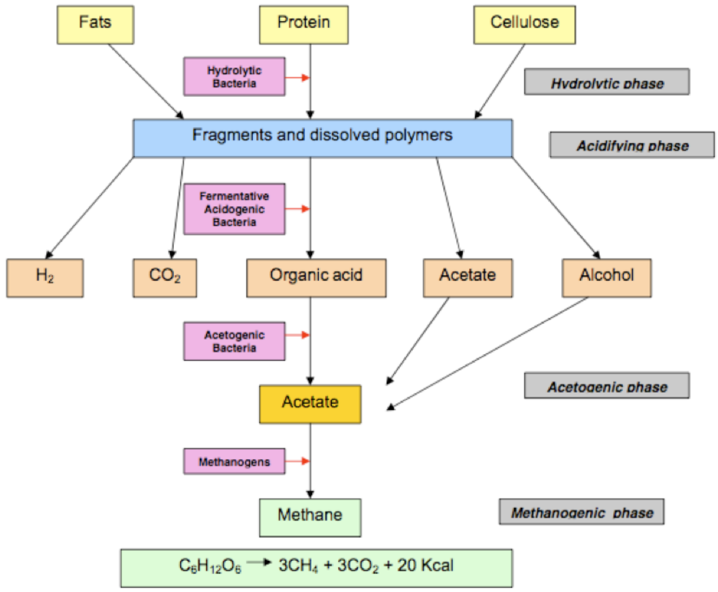
Digesting of bio-organic substances anaerobically

Digesting process is in liquid state fermentation (LSF) under some requirements:

- **Oxygen**
- **Temperature**
- **pH**
- **Substrate availability**
- **Inhibitor substances**

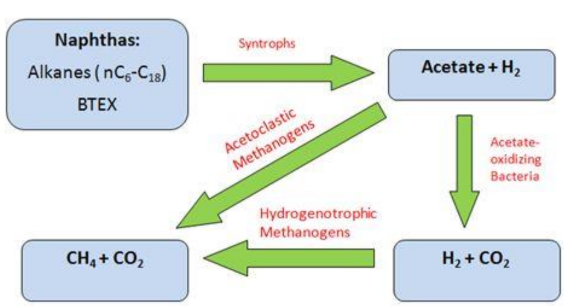


Steps / phase in biogas production process



Microbes involve in each step of biogas production

No	Type of microbes	Microbes
1	Hydrolysis	*Bacteriocides, Clostridia, Bifidobacteria*
2	Fermentative acidogenic	*Streptococci, Enterobacteriaceae* (facultative anaerobic)
3	Acetogenic	*Acetobacterium woodii, Clostridium aceticum*
4	Methanogenic	*Methanosarcina barkeri, Metanonococcus mazei, Methanotrix soehngenii* (strictly anaerobic)



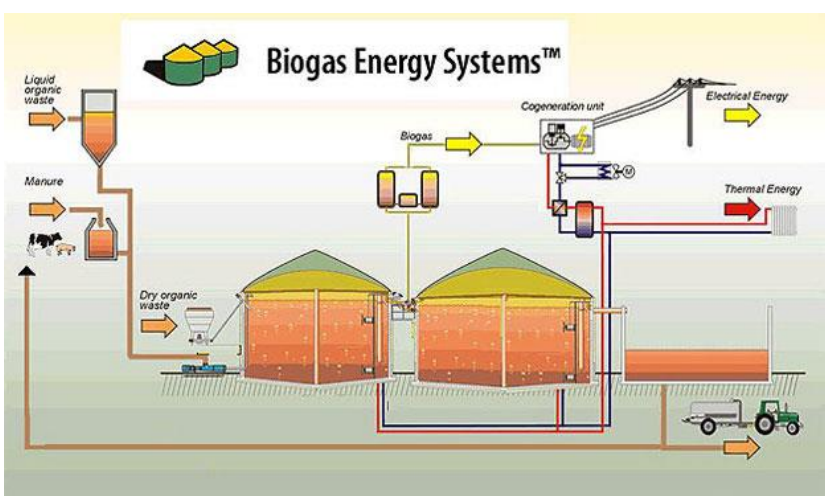
Digesting of bio-organic substances anaerobically

Digesting process is in liquid state fermentation (LSF) under some requirements:

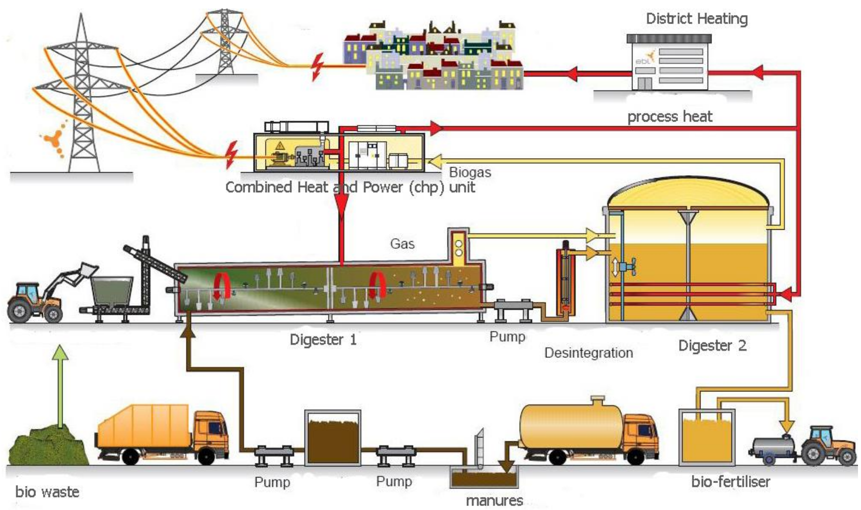
- **Oxygen** *(the oxygen should be very low or in anaerobic condition).*
- **Temperature** *(most of methane bacteria is mesophyle, 32-42°C)*
- **pH-value** *(hydrolysis and acid forming process at low pH, 4.5-6.3, while acetic acid and methane forming process at neutral pH, 6.8-7.5)*
- **Substrate availability** *(C:N:P:S condition is 600:15:5:1)*
- **Inhibitor substances** (some inhibitor substances during fermentation of methane production)

Inhibitors	Concentration
Sodium	6-30 g/L (for some adapt bacteria culture until 60 g/L)
Potassium	Starting at 3 g/L
Calcium	Starting at 2.8 g/L $CaCl_2$
Magnesium	Starting at 2.4 g/L $MgCl_2$
Ammonium	2.7-10 g/L
Ammonia	Starting at 0.15 g/L
Sulfur	Starting at 50 mg/L H2S, 100 mg/L S2-, 160 mg/L Na2S (for some adapt bacteria culture until 600 mg/L Na_2S and 1,000 mg/L H_2S)
Heavy metals	As free ions, starting at 10 mg/L Ni, 40 mg/L Cu, 130 mg/L Cr, 340 mg/L Pb, 400 mg/L Zn As carbonate form, starting at 160 mg/L Zn, 170 mg/L Cu, 180 mg/L Cd, 530 mg/L Cr^{3+}, 1,750 mg/L Fe. Heavy metals can be by sulfite sedimented and neutralized
Branch fatty acid	Iso-butyric acid: starting at 50 mg/L

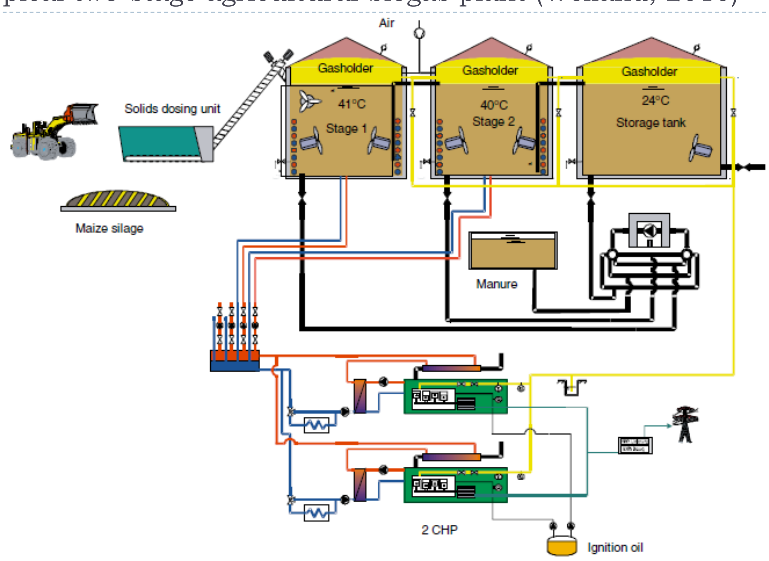
Flow-storage process of biogas



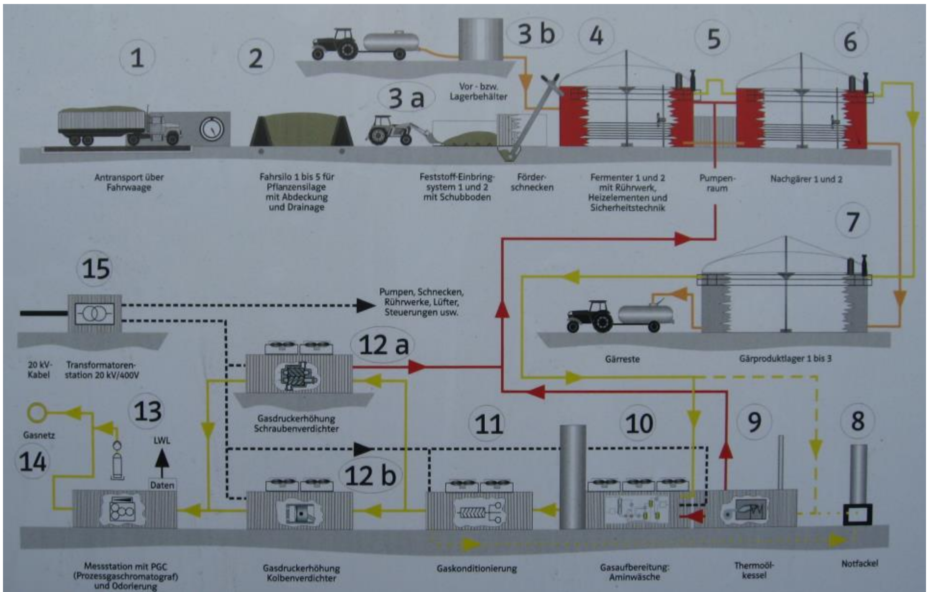
Flow-storage process of biogas



Typical two-stage agricultural biogas plant (Weiland, 2010)

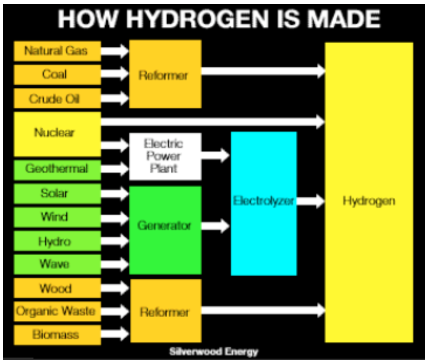


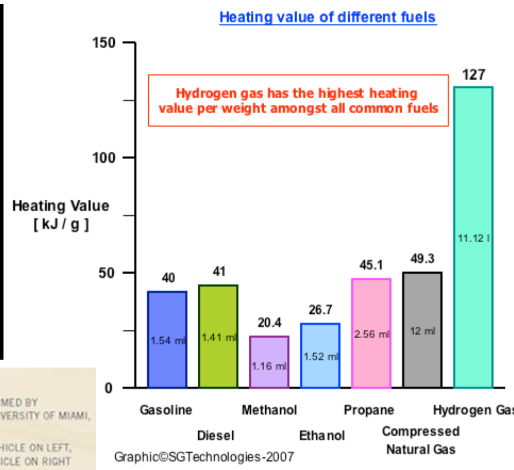
Flow-storage process of biogas at e-on company near Hannover, Germany

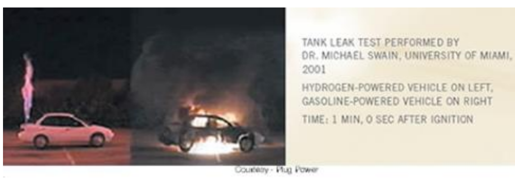


Biogas Plant

Hydrogen characteristics



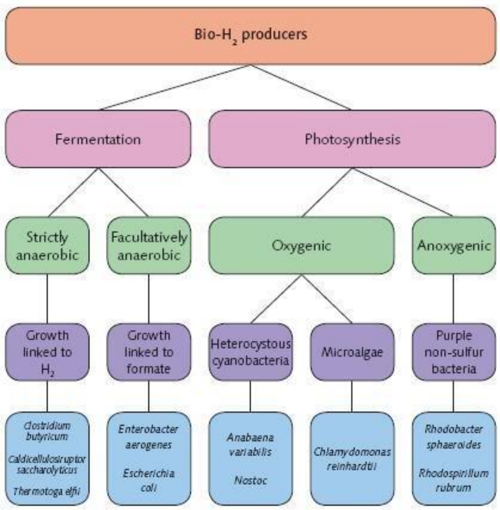


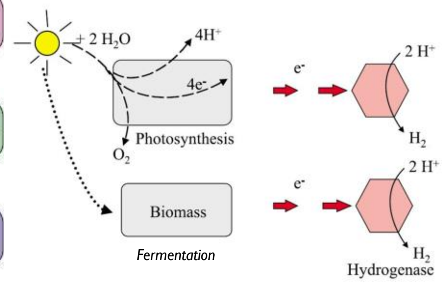


Hydrogen characteristics

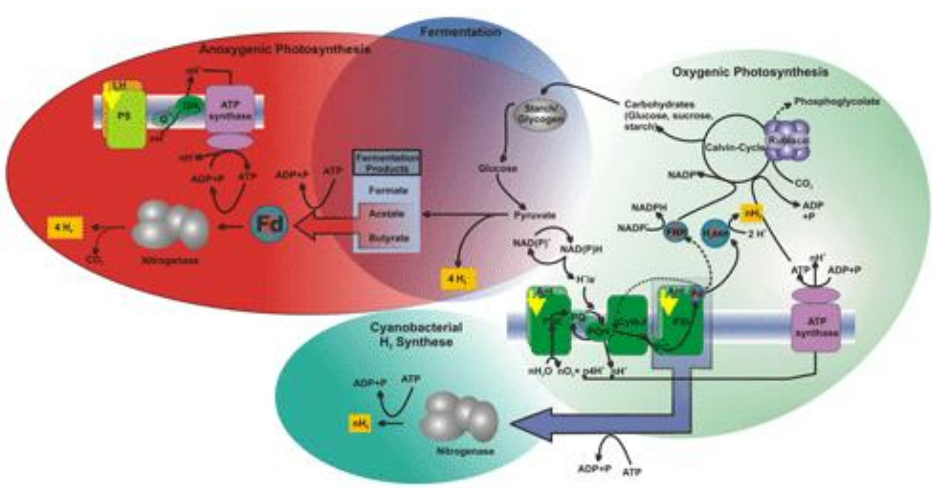
- Clean energy source, producing water as its only by-product when it burns.
- Can be produced from renewable raw materials (biologically) such as organic wastes (*compost, anaerobic digester sludge, food and starch-based wastes, cellulosic materials, dairy wastes, palm oil mill effluent, and glycerol*), called biohydrogen.
- Biohydrogen process not only generates environmentally clean energy - hydrogen, but also stabilizes the waste.
- The biohydrogen fermentation technology could enhance the economic viability of many processes utilizing hydrogen as a fuel source or as a raw material.

Biohydrogen production method



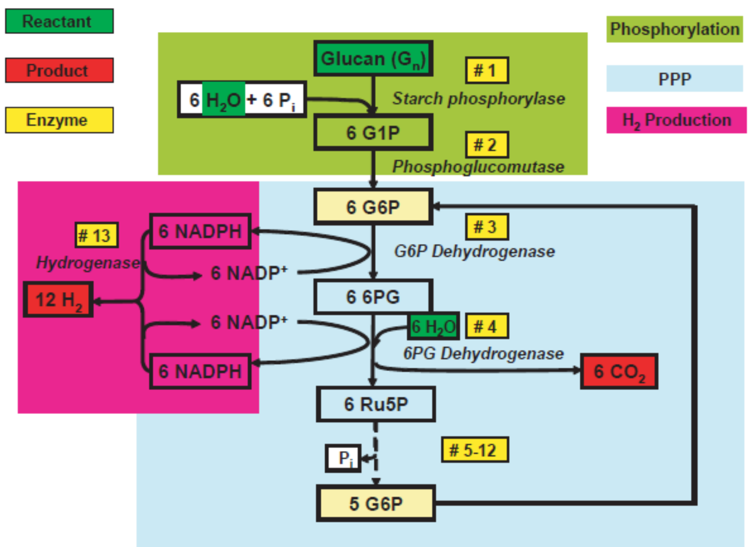


Biohydrogen metabolic pathway



The production of H_2 is one of the specific mechanisms to dispose excess electrons through the activity of hydrogenase enzymes present in H_2 producing microorganisms. Hydrogenases have various physiological roles

The synthetic metabolic pathway of polysaccharide and water to hydrogen and carbon dioxide



Terms of Biohydrogen

- Biohydrogen, biologically produced hydrogen from renewable sources (biomass, water, organic wastes).
- Biohydrogen production:
  - Photosynthetic (cyanobacteria and algae)
  - Fermentative
    - Photofermentation (purple bacteria; / photosynthetic bacteria)
    - Dark fermentation (fermentation without light)
- They may also have different localization in the cell and different subunit composition.
- Three main classes:
  - iron-only ([FeFe] hydrogenases)
  - nickel-iron ([NiFe] hydrogenases)
  - "iron-sulphur-cluster-free" hydrogenases (contain no redox active metal ion in their active center).

Biohydrogen production by dark fermentation

- Classified into two categories:
  - Facultative anaerobes (enteric bacteria, e.g. *Escherichia coli, Enterobacter*, and *Citrobacter*)
  - Strict anaerobes (clostridia, methylotrophic methanogens, and rumen bacteria). The extreme thermophile *Caldicellulosiruptor saccharolyticus* is related to clostridia.
- The genus Clostridium has been widely studied for H_2 production, capable of using various organic substrates such as proteins, starch, animal manure and sewage sludge. Some clostridia are both proteolytic and saccharolytic.
- The fermentative route is a promising method for biohydrogen production due to its high rate of the H_2 evolving [FeFe] hydrogenase and the versatility of the substrates used.

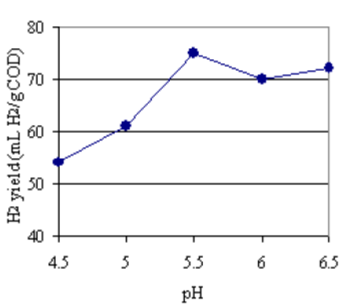
Optimization of biohydrogen production of *C. butyricum* EB6

- Using synthetic medium was done on pH, glucose and iron concentration
- Optimum production achieved at
  - pH 5.6,
  - 15.7 g/L glucose and
  - 0.39 g/L FeSO4
- Yield of biohydrogen at 2.2 mol H_2/mol glucose

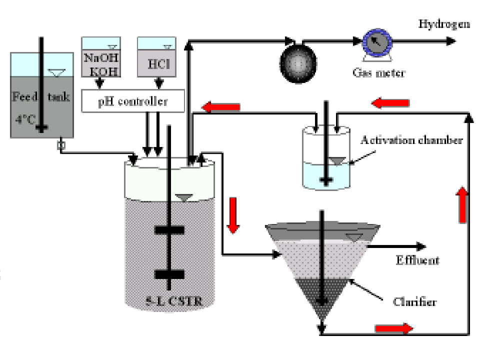
Improving genetic characteristic of microbe expresse hydrogenase

- [Fe]-hydrogenase (*hyd*A) gene of *C. butyricum* EB6
  - open reading frames of 1725 bp
  - encodes *hyd*A of 574 amino acids
  - approximate size of 64 kDaltons
  - The *hydA* of *C. butyricum* was found 80.5% similar to *hydA* of *C. acetobutylicum* P262 and closely similar to *Clostridia* hydrogenase.
  - A *hydA*-expressing recombinant EB6 was successfully obtained with higher biohydrogen production of 4.2-4.8 L-H_2/ L-medium compared to the wild type

Hydrogen production

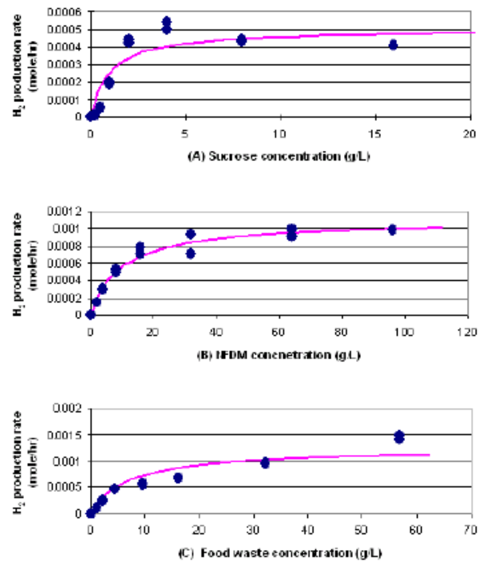


Effect of pH on hydrogen production in batch studies

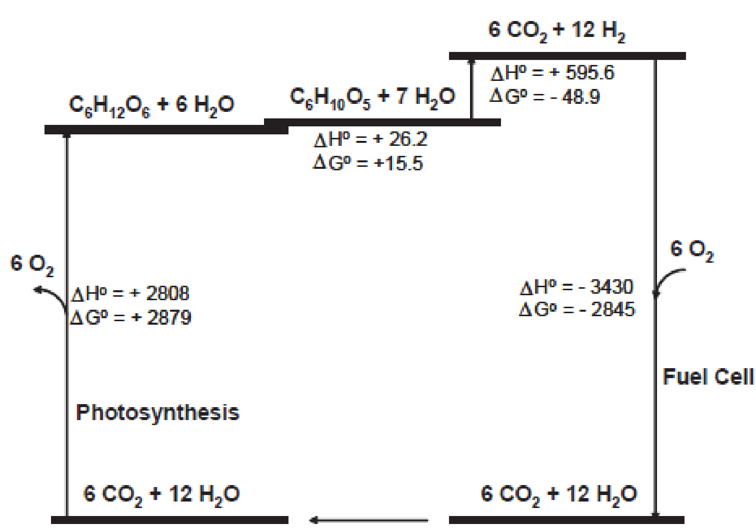


Experimental setup of continuous bioreactor

Biohydrogen production rates at various initial substrate concentration (A) Sucrose; (B) Non-Fat Dry Milk; (C) Food Waste



An energy diagram showing the standard enthalpy and free energy changes in kJ/mol for reaction in a renewable energy cycle operating among H_2O, CO_2, glucose, and starch



The enzymes used for hydrogen production from starch and water, and reaction mechanism, sources, and amounts use in the reaction

E.C.	Enzyme Name	Reaction	Vender	Origin	Unit
2.4.1.1	glycogen phosphorylase	$(C_6H_{10}O_5)_n + P_i + H_2O \rightarrow (C_6H_{10}O_5)_{n-1}$ + glucose-1-P	Sigma	rabbit muscle	10
5.4.2.2	phosphoglucomutase	G-1-P→G-6-P	Sigma	rabbit muscle	10
1.1.1.49	glucose-6-phosphate dehydrogenase	G-6-P+$NADP^+$→6-phosphogluconate+NADPH	Sigma	*S. cerevisiae*	1
1.1.1.44	6-phosphogluconic dehydrogenase	6-phosphogluconate+H_2O+$NADP^+$→ribulose-5-phosphate+NADPH+CO_2	Sigma	*S. cerevisiae*	1
5.3.1.6	ribose 5-phosphate isomerase	ribulose-5-phosphate→ribose-5-phosphate	Sigma	spinach	1
5.1.3.1	ribulose-5-phosphate 3-epimerase	ribulose-5-phosphate→xylulose-5-phosphate	Sigma	*S. cerevisiae*	1
2.2.1.1	transketolase	xylulose-5-phosphate+ribose-5-phosphate→sedoheptulose-7-phosphate+glyceraldehyde-3-phosphate	Sigma	E. coli	1
		xylulose-5-phosphate+erythrose-4-phosphate→fructose-6-phosphate+glyceraldehyde-3-phosphate			
2.2.1.2	transaldolase	sedoheptulose-7-phosphate+glyceraldehyde-3-phosphate→fructose-6-phosphate+erythrose-4-phosphate	Sigma	*S. cerevisiae*	1
5.3.1.1	triose-phosphate isomerase	glyceraldehyde 3-phosphate→dihydroxacetone phosphate	Sigma	rabbit muscle	1
4.1.2.13	aldolase	glyceraldehyde 3-phosphate+dihydroxacetone phosphate→fructose-1,6-bisphosphate	Sigma	rabbit muscle	1
3.1.3.11	fructose-1,6-bisphosphate	fructose-1,6-bisphosphate+H_2O→fructose-6-phosphate+Pi	[41]	*E. coli*	1
5.3.1.9	phosphoglucose Isomerase	fructose 6-phosphate→glucose-6-P	Sigma	*S. cerevisiae*	1
1.12.1.3	*P. furiosus* hydrogenase I	NADPH+H^+→$NADP^+$+H_2	[22.42]	*P. furiosus*	~70