

Different pathways of resource recovery from anaerobic digestion of organic residues

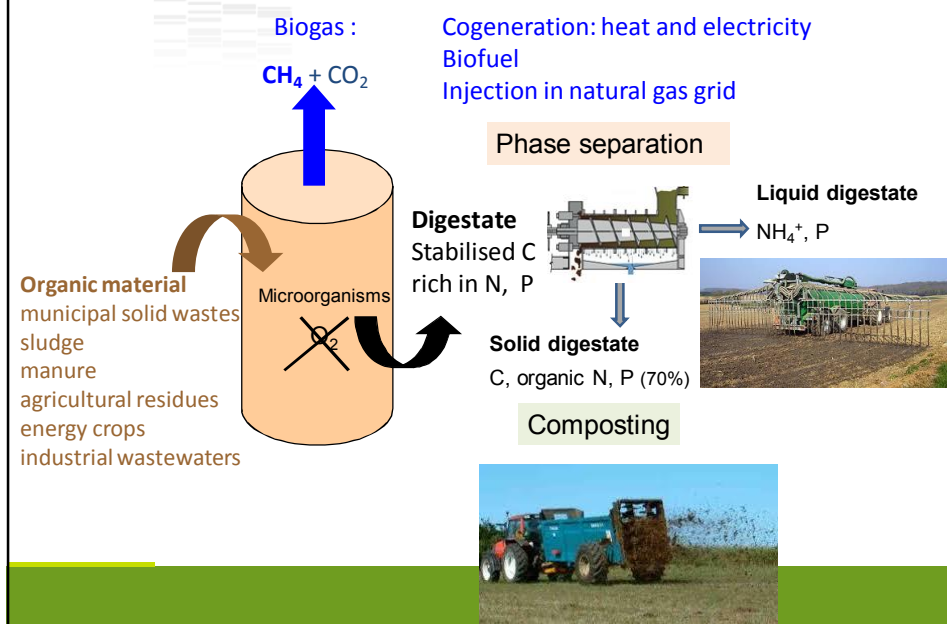
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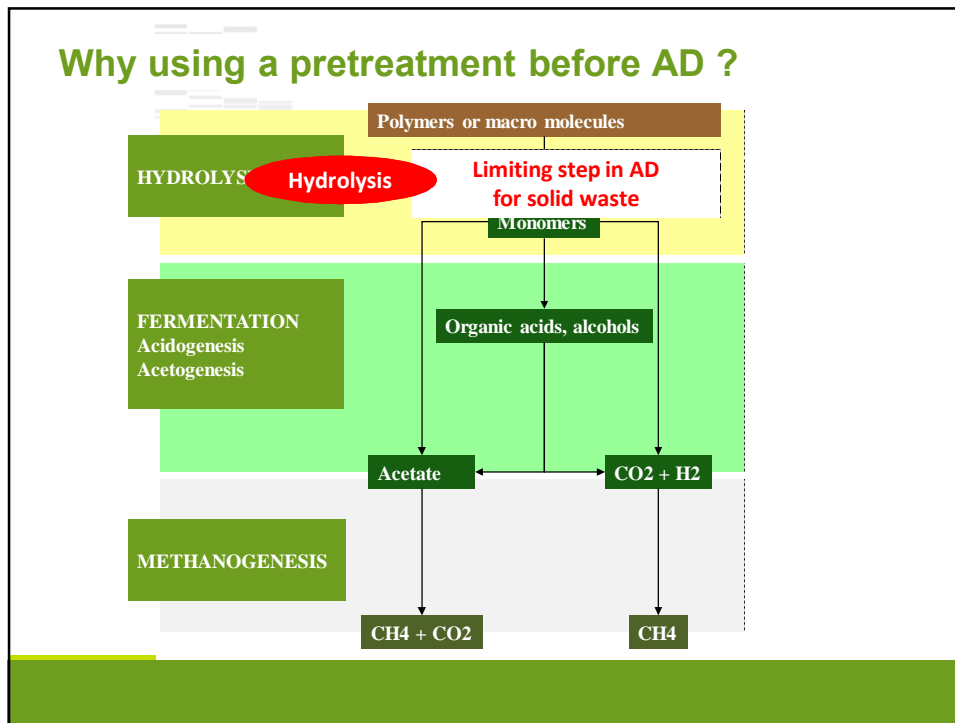
Anaerobic digestion : the classical pathway



Outline

- 1. Producing more methane**
 - Interest of pretreatments
- 2. Producing other molecules**
 - Hydrogen, carboxylic acids, solvents via dark fermentation process and pretreatments
- 3. New opportunities of digestate valorization**
 - Liquid digestate
 - Solid digestate

1- Interest of pretreatments for methane production



Why using a pretreatment before AD ?

- ❖ Biodegradable compounds are hardly accessible to micro-organisms
 - intracellular compounds of sewage sludge or microalgae
 - sugars from lignocellulosic biomass
 - fatty residues
- ❖ Waste sanitation
- ❖ To transform refractory compounds
- ❖ To remove/transform inhibitors
- ❖ To concentrate wastes with low methane potential

The consequences of pretreatments

- 😊😊 Increase of methane potential (BMP) or methane yield
(L CH₄ /kg TS or VS)
- 😊 Increase of anaerobic digestion rate
decrease of hydraulic retention time (HRT) in the digester
- 😞 Loss of biodegradable compounds
- 😞😞 Release of recalcitrant/inhibiting compounds

Pretreatments (PT) of municipal solid wastes

- ❖ Many studies based on **Biochemical Methane Potential (BMP)**
→ wide range of BMP increase (0 -120%)

Cesaro and Belgiorno, ppreatment methods to improve anaerobic biodegradability of organic municipal solid waste fractions, Chemical Engineering Journal, 240 (2014) 24-37
Zhang, Su, Bayens and tan Reviewing the anaerobic digestion of food waste for biogas production, Renewable and Sustainable Energy Reviews, 38 (2014) 383-392

PT performance in full scale cannot be extrapolated from BMP results

BMP

- Batch
- Diluted medium
- Lasts until total conversion

Full scale anaerobic digestion

- Continuous
- High TS content (dry AD)
- HRT : 10-30 d
- Impact of PT on methane yield and AD rate

→ **Need of experiments in continuous reactors or modelling procedure to assess full scale performance**

Souza, T.S.O., Carvajal, A., Donoso-Bravo, A., Pena, M., Fdz-Polanca, F. 2013. ADM1 calibration using BMP tests for modeling the effect of autohydrolysis pretreatment on 47(9), 3244-3254

Pretreatments of municipal solid wastes

❖ Few studies on lab- or pilot- scale **continuous reactors**

- Extrusion → 800 L biogas/ kg VS
- Shear shredder → increase of AD rate but not of biogas yield
acidification and process failure in dry AD
- Composting 1 day → + 73% biogas in dry AD
- Composting (auto-heating up to 60°C, 2-7 days)
 - + 32% biogas in dry AD with low OLR, high HRT
 - -11% biogas in dry AD with high OLR, low HRT
 - -28% biogas if 6 d composting (CO₂ losses)

Novarino & Zanetti, 2012

Zhang & Banks 2013

Fernandez-Guelfo et al., 2011

Mata-Alvarez et al., 1993, Charles et al., 2009

Pretreatments of municipal solid wastes

❖ **At full scale**

- **mechanical pretreatments**
used for waste sorting and to ease feeding
- **thermal pretreatment / Steam explosion**
applied to municipal solid wastes in codigestion (sludge)
One plant treating MSW in Lillehammer (Norway)
 - reduction of viscosity,
better separation of unwanted wastes (plastics)
 - 1000 kg MSW, 620 kg after sorting
 - 60 m³ CH₄ and 150 kg digestate



Cambi™

Panter et al., 2007, Hydrolysis and digestion of biodegradable Municipal waste at Lillehammer, Norway - 2 years full scale experience. <http://www.cambi.com/publications/biowaste>

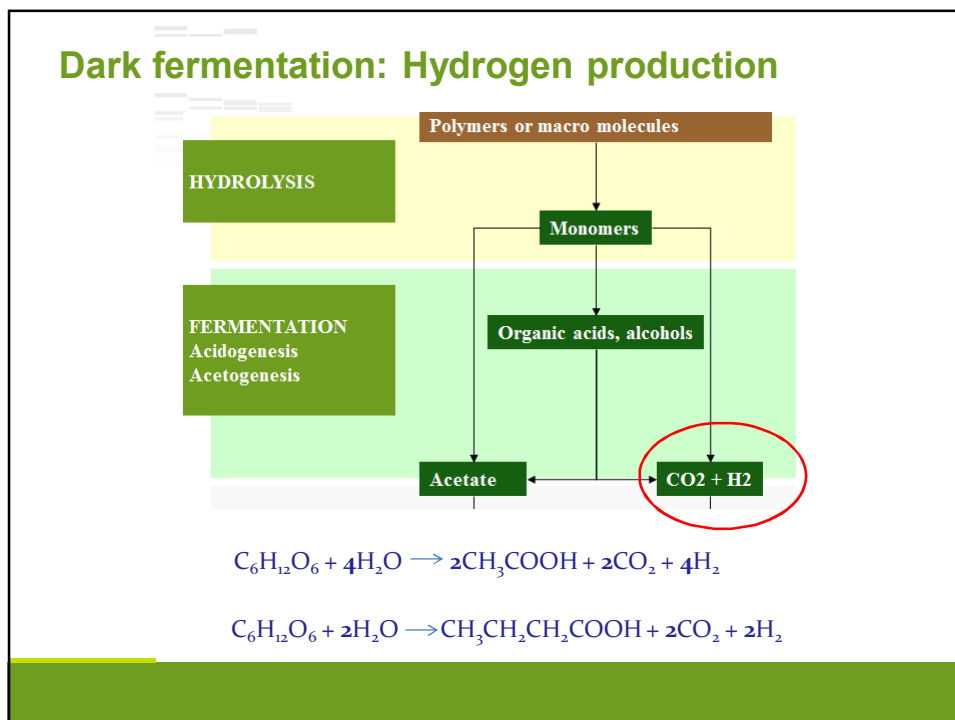
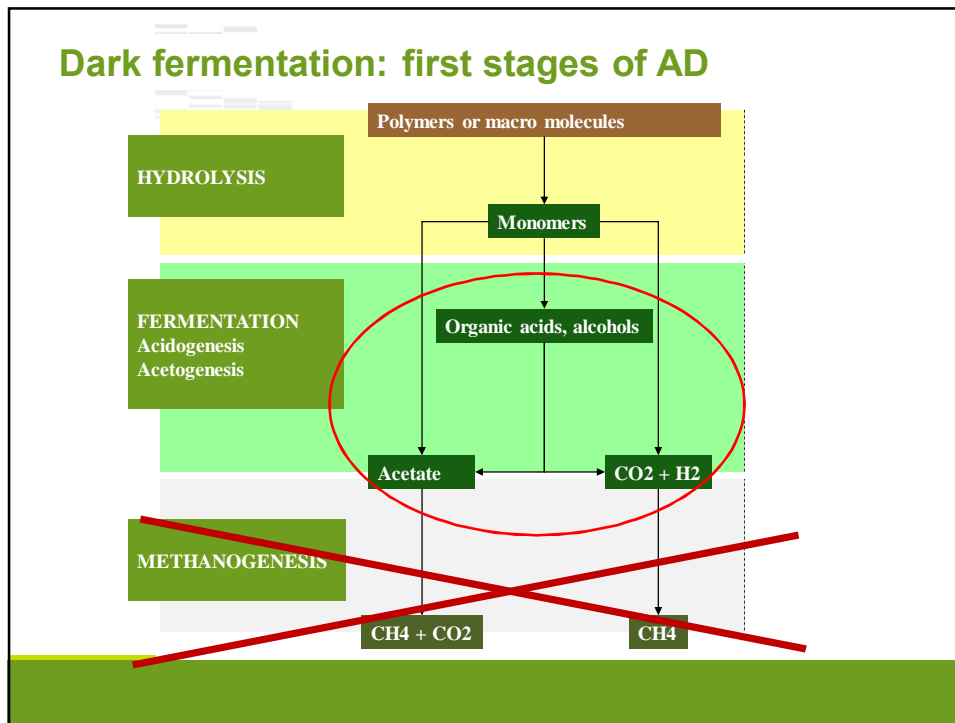
Pretreatments before anaerobic digestion-conclusion

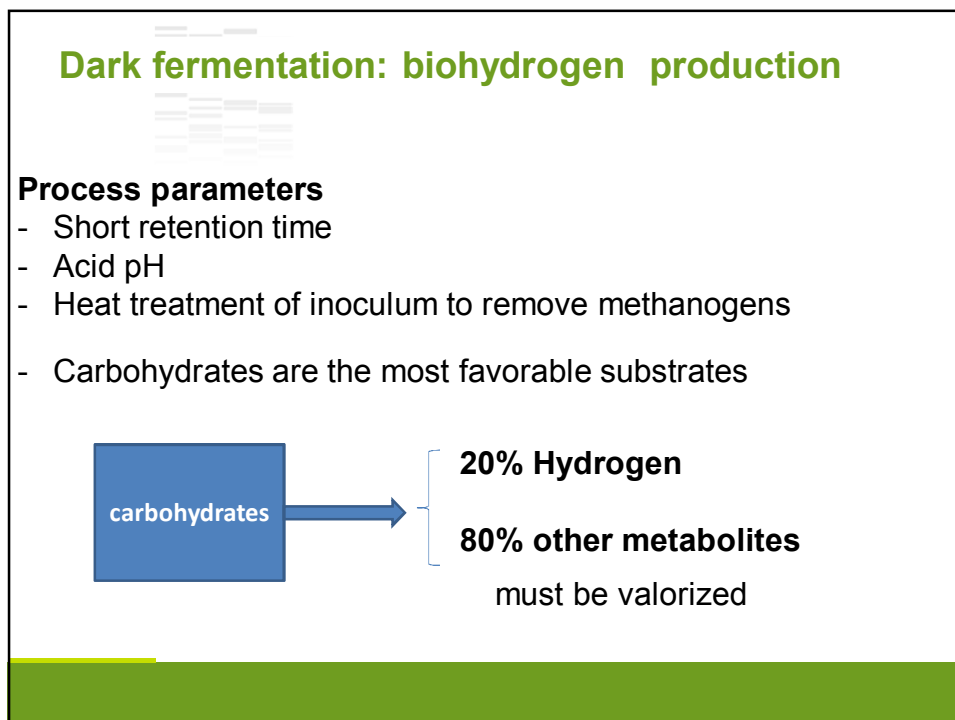
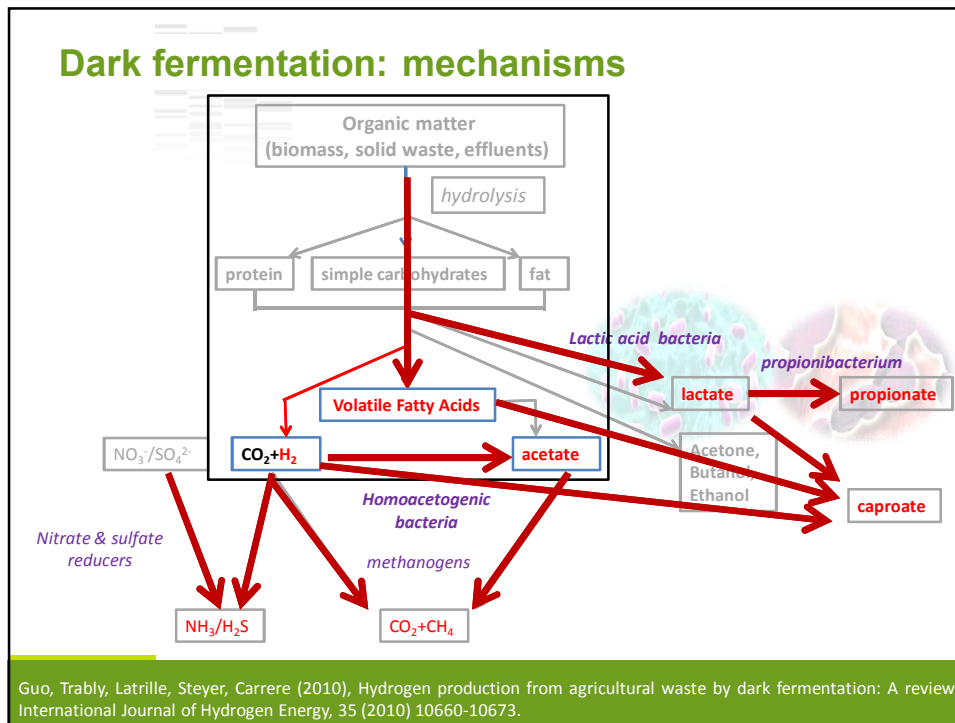
Pretreatments in full scale AD plants are mainly applied to

- sewage sludge to reduce sludge disposal costs
e.g. thermal, sonication, high pressure...
- animal by-product for sanitation
e.g. thermal
- agricultural effluents to increase temperature before batch AD
(composting) and to ease feeding of continuous AD (grinding)
- municipal solid wastes to ease sorting and feeding

→ **Interest of optimising such compulsory pretreatments
for increasing methane production with low costs and
environmental footprint**

2- Production of other molecules : dark fermentation and pretreatments





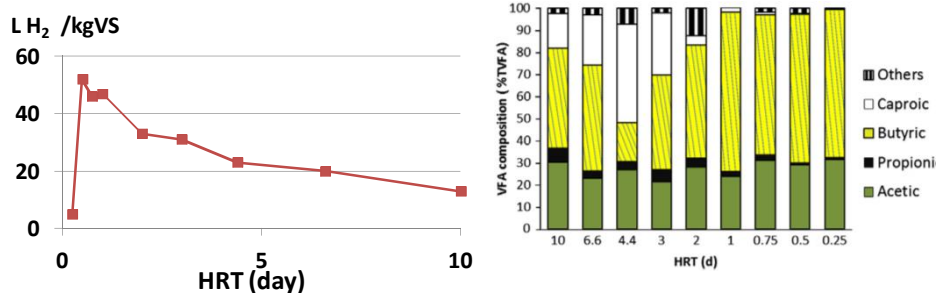
Dark fermentation of municipal solid wastes

Hydrogen production

- Biohydrogen potential of MSW : 40-180 mL H₂·g VS⁻¹

Bru, et al. Innovative CO₂ pretreatment for enhancing biohydrogen production from the organic fraction of municipal solid waste (OFMSW). International Journal of Hydrogen Energy. 2012;37:14062-71.

- Impact of hydraulic retention time



Zahedi et al. Hydrogen production from the organic fraction of municipal solid waste in anaerobic thermophilic acidogenesis: content of the solid waste. Bioresource Technology. 2013;129:85-91.

Pretreatments to improve hydrogen production

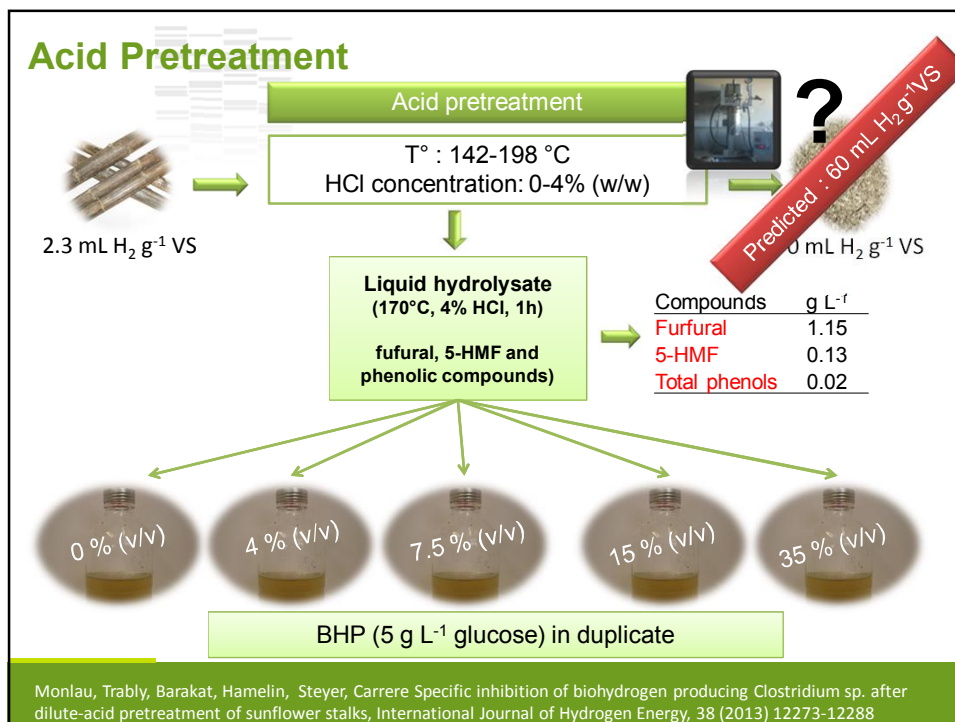
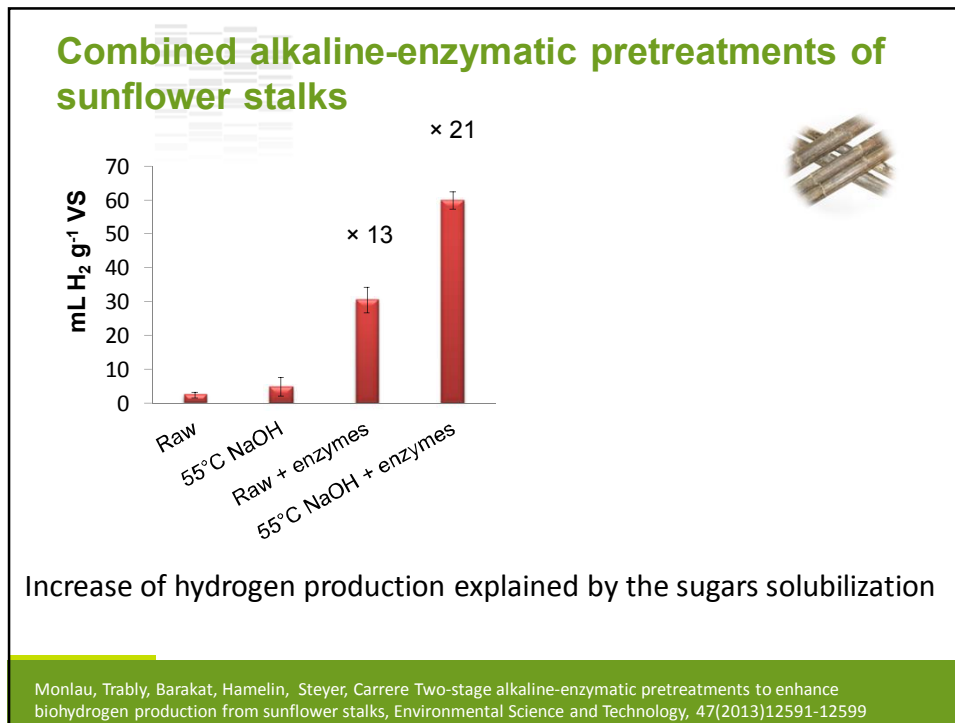
Main purpose of the pretreatment is carbohydrates solubilization

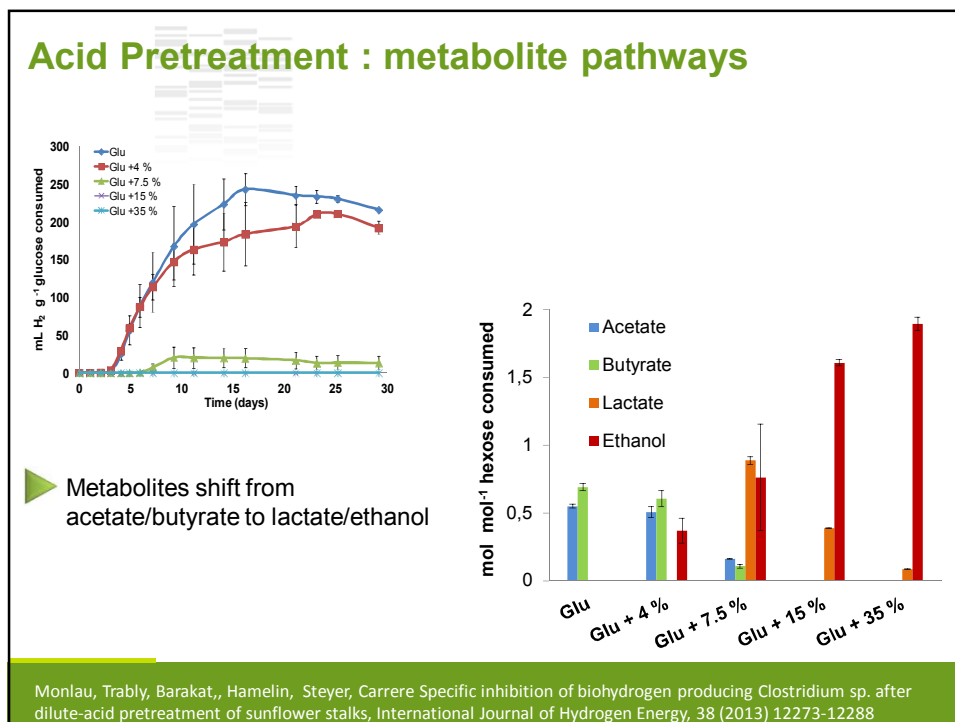
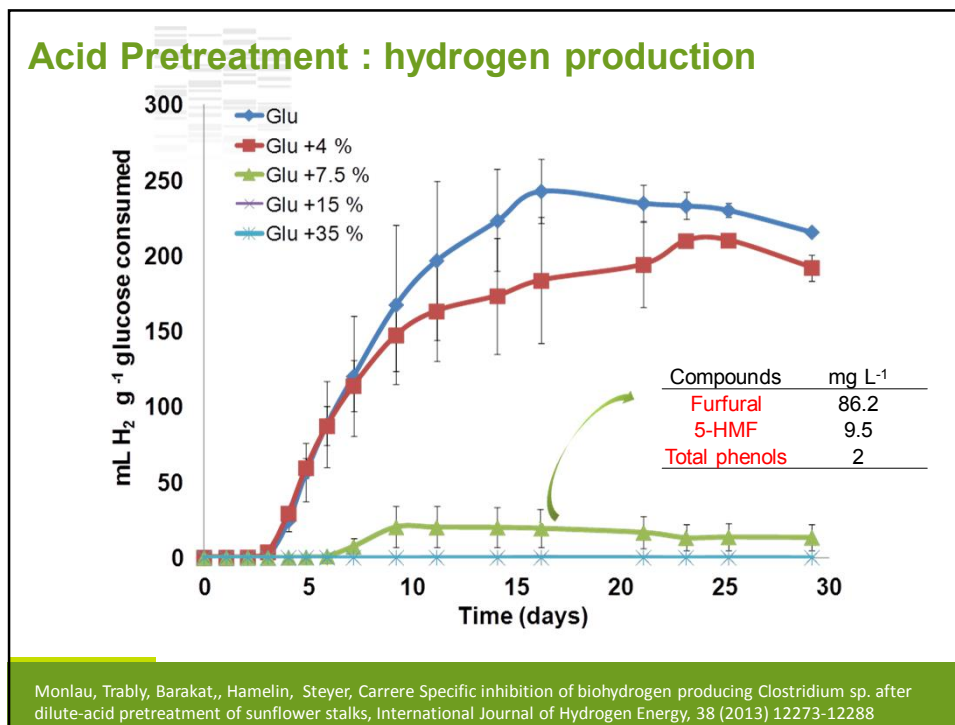
- ✓ Avoid the degradation or loss of carbohydrates;
- ✓ Avoid the formation of inhibitory byproducts;
- ✓ Be cost-effective.

▶ Enzymatic , alkaline-enzymatic

▶ Acid

Monlau F, Sambusiti C, Barakat A, Guo X M, Latrille E, Trably E, Steyer J P, Carrere H. Predictive models of biohydrogen and biomethane production based on the compositional and structural features of lignocellulosic materials. Env Sci Tech 2012; 46(21): 12217-12225.





Dark fermentation: carboxylic acid production

Table 5. Comparison of the Experimental Results with Literature Data of Anaerobic Fermentation of OFMSW*

process	T °C	HRT d	OLR kg V S m ⁻³ d ⁻¹	yields gSCOD gVS _{fed} ⁻¹	VFA/SCOD %	ref
BATCH	15-20	4.5	40	0.27	13	this study
BATCH	35	1	92	0.54	50	Traverso et al. ⁷
CSTR	35	1.5-6	82-85	0.48-0.55	55-90	Traverso et al. ⁷
CSTR	35	1.5-6	4.5-18	0.43-0.56		Andreottola et al. ¹⁷
PFR	37	2-6	38-85	0.5	30-60	Sans et al. ⁴
CSTR	37	1.5-8.5	2-25	0.4-0.5	38-73	Argelier et al. ⁶
CSTR	55	1-5	19-78	0.50-0.90	50-65	Pavan et al. ²³

* PFR = plug-flow reactor, CSTR = continuously stirred tank reactor.

Bolzonella D, Fatone F, Pavan P, Cecchi F. Anaerobic fermentation of organic municipal solid wastes for the production of soluble organic compounds. *Industrial & Engineering Chemistry Research*. 2005;44:3412-8.

OLR = 20 g VS. L⁻¹.day⁻¹

VFA concentration 15 g L⁻¹ (as acetic acid)

75 % acetic,

12 % caproic

6% butyric

But need of downstream processing

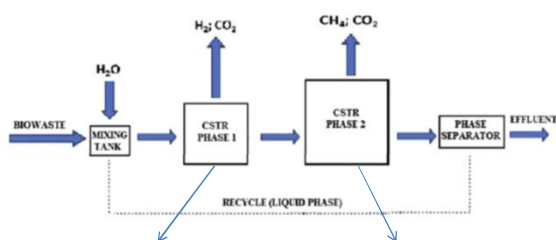
Dogan E, Demirer GN. Volatile Fatty Acid Production from Organic Fraction of Municipal Solid Waste Through Anaerobic Acidogenic Digestion. *Environmental Engineering Science*. 2009;26:1443-50.

Methane production from dark fermentation effluent

Biohythane

5-20% H₂ in CH₄
- better combustion
- less emissions

Pilot plant in
wastewater
treatment plant in
Treviso-Italy



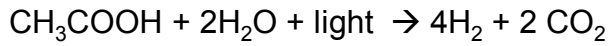
CSTR 200 L
55°C
HRT=3.3 d
pH= 5.5-6
67 L H₂ kg⁻¹VS

CSTR 760 L
55°C
HRT=12.6 d
pH= 8
482 L CH₄ kg⁻¹VS

Cavinato C, Giuliano A, Bolzonella D, Pavan P, Cecchi F. Bio-hythane production from food waste by dark fermentation coupled with anaerobic digestion process: A long-term pilot scale experience. *International Journal of Hydrogen Energy*. 2012;37:11549-55.

Hydrogen production from dark fermentation effluent

Photofermentation

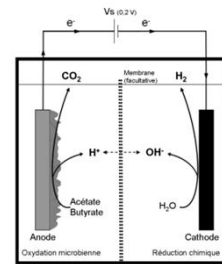


Purple bacteria *Rhodobacter* sp.



Uyar, et al. Photofermentative hydrogen production from volatile fatty acids present in dark fermentation effluents, Int. J. Hydrogen Energy, 2009 (10) 4517-4523, Obeyd et al., State estimation of a batch hydrogen production process using the photosynthetic bacteria *Rhodobacter captulatus*, Int. J. Hydrogen Energy, 2010 (19) 10719-10724

Microbial electrochemical cells



Pierra M, Trably E, Godon JJ & N Bernet (2013) Fermentative hydrogen production under moderate halophilic conditions. International Journal of Hydrogen Energy

Use of carboxylic acid for biological nutrient removal

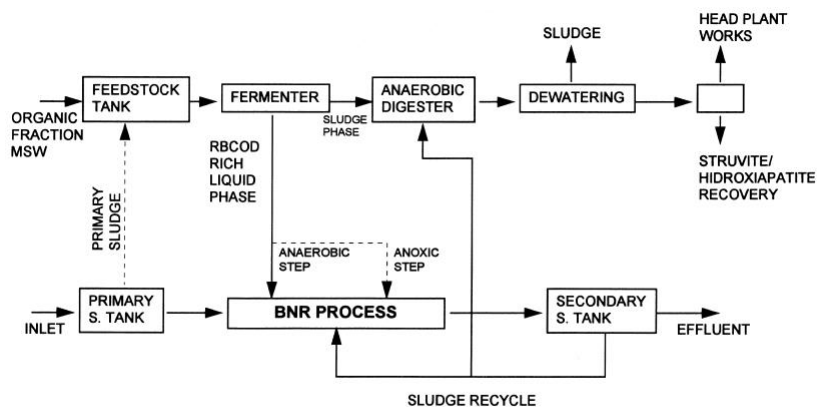


Fig. 1. Sketch of a possible integrated municipal wastes treatment. Phosphates are removed via struvite recovery.

Llabres P, Pavan P, Battistioni P, Cecchi F, Mata-Alvarez J. The use of organic fraction of municipal solid waste hydrolysis products for biological nutrient removal in wastewater treatment plants. Water Research. 1999;33:214-22.

Chain elongation of carboxylic acid

medium chain fatty acid (MCFA for building blocks)

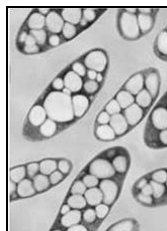
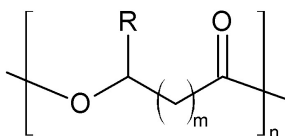


	Input (g/L)	Output (g/L)
Ethanol	19.3	3.7
nC2	3.3	1.3
nC3	1.8	0.5
nC4	1.9	3.2
nC5	1.1	2.0
nC6	0.7	12.6 caproate
nC7	0.4	0.9
nC8	0.0	0.4

Grootscholten TIM, Strik D, Steinbusch KJJ, Buisman CJN, Hamelers HVM. Two-stage medium chain fatty acid (MCFA) production from municipal solid waste and ethanol. *Applied Energy*. 2014;116:223-9.

Production of polyhydroxyalkanoates (PHA) from carboxylic acids

- replacement potential over conventional polyolefins
- conversion of small carboxylic acids to PHA by
 - mixed aerobic bacterial consortia
 - alternation of substrate excess and limitation



Albuquerque MGE, Martino V, Pollet E, Averous L, Reis MAM. Mixed culture polyhydroxyalkanoate (PHA) production from volatile fatty acid (VFA)-rich streams: Effect of substrate composition and feeding regime on PHA productivity, composition and properties. *Journal of Biotechnology*. 2011;151:66-76

Dark fermentation-conclusion

Demonstration of hydrogen production from MSW at pilot scale

Necessity to valorize dark fermentation effluents (carboxylic acids)

- Anaerobic digestion
- Higher value of VFA but need of downstream processing
- Bioconversion of VFA
 - in hydrogen (bioelectrochemical systems)
 - in middle chain acids
 - in polymers

3- New opportunities for digestate valorization

Methane production from digestate

Litterature review on full-scale agricultural biogas plants

BMP of digestates : 60-110 L CH₄/kg VS

BMP of digestate solid fraction : 60-160 L CH₄/kg VS

Various physico chemical and biological treatment of digestate before BMP

- Lower BMP in some cases
- Some BMP increased up to 300 L CH₄/kg VS

Monlau F, Sambusiti C, Ficara E, Aboulkas A, Barakat A, Carrere H. New opportunities for agricultural digestate valorization: current situation and perspectives. *Energy & Environmental Science*. 2015;8:2600-21.

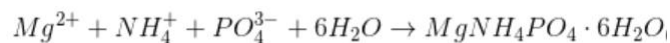
Liquid fraction of digestates

Water recovery

- membrane technologies

Recovery of Nutrients

- e.g. as struvite precipitation



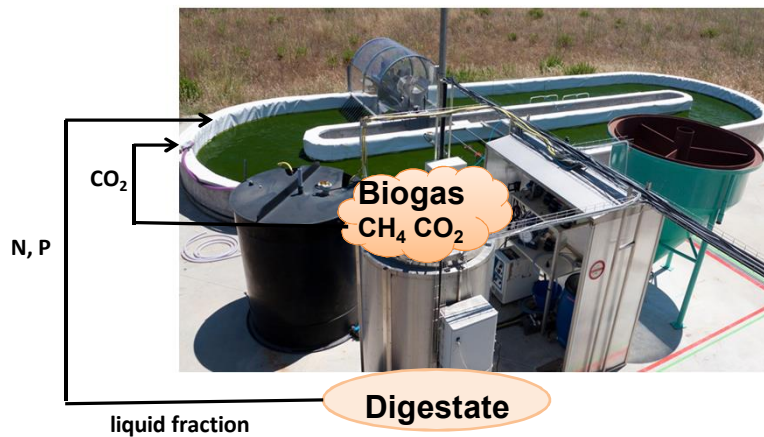
Malamis, Katsou, Di Fabio, Bolzonnella, Fatone. Biological nutrients removal from the supernatant originating from the anaerobic digestion of the organic fraction of municipal solid waste, *Critical reviews in biotechnology*, 34(2014) 244-257

Use as nutrients source for

- ethanol fermentation
- algae growth (after dilution)

Monlau F, Sambusiti C, Ficara E, Aboulkas A, Barakat A, Carrere H. New opportunities for agricultural digestate valorization: current situation and perspectives. *Energy & Environmental Science*. 2015;8:2600-21.

Combination of AD and algae growth



Uggetti, Sialve, Trably, Steyer, Integrating microalgae production with anaerobic digestion: a biorefinery approach
Biofuel Bioproducts & Biorefinery, 8 (20134) 516-529

Solid fraction of digestates

Ethanol production

digestates from lignocellulosic biomass enriched in cellulose
alkali treatment,
enzymatic hydrolysis,
fermentation

➔ 80-100 g_{Ethanol}/kg_{TS} digestate

Z. Yue, C. Teater, J. MacLellan, Y. Liu and W. Liao, Biomass Bioenergy, 2011, 35, 1946–1953.

Thermal conversion of solid digestates

Hydrothermal carbonization

high moisture (>80%)

180-250°C, 10-40 bars

➡ main product: hydrochar

Pyrolysis

low moisture

500-800°C, oxygen free atmosphere

➡ main products: syngas H₂, CO and others
bio-oil
pyrochar

Use of hydro- pyro-chars

solid fuel

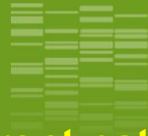
soil improver

adsorbant / activated carbon precursor

Monlau F, Sambusiti C, Ficara E, Aboulkas A, Barakat A, Carrere H. New opportunities for agricultural digestate valorization: current situation and perspectives. Energy & Environmental Science. 2015;8:2600-21.

TAKE-HOME-MESSAGE

- ❖ Many alternatives for municipal solid waste valorization based **anaerobic digestion** process
a key process for environmental biorefinery
- ❖ At present limited use of municipal solid waste digestate
Interest of combining
algae production for liquid fraction
with thermal process for solid fraction
- ❖ Anaerobic digestion of municipal solid waste development
requires further efforts both in research and waste sorting



Thank you for your attention...

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