Archaea Biotechnology

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What is Biotechnology?

- **Any technological application using biological systems, living organisms, or derivatives thereof, to manufacture or modify products or processes for specific use.**

Biotechnology

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Area	Application in
Green biotechnology	Agriculture, plant biotechnology, forestry, food science
Red biotechnology	Medicine, pharmaceutics, nanobiotechnology
White Biotechnology	Industrial biotechnology, industrial (bio)chemistry, industrial bioprocessing, biorefinery
Grey biotechnology	Environmental biotechnology, waste (water) management and treatment, biorefinery, renewable energy production
Blue biotechnology	Seafood and freshwater food production; supply, safety and control of aquatic organisms
Yellow biotechnology	Insect biotechnology, food science and technology

- **Currently archaea (or componets thereof) are or could be applied in the area of red, white and grey biotechnology**

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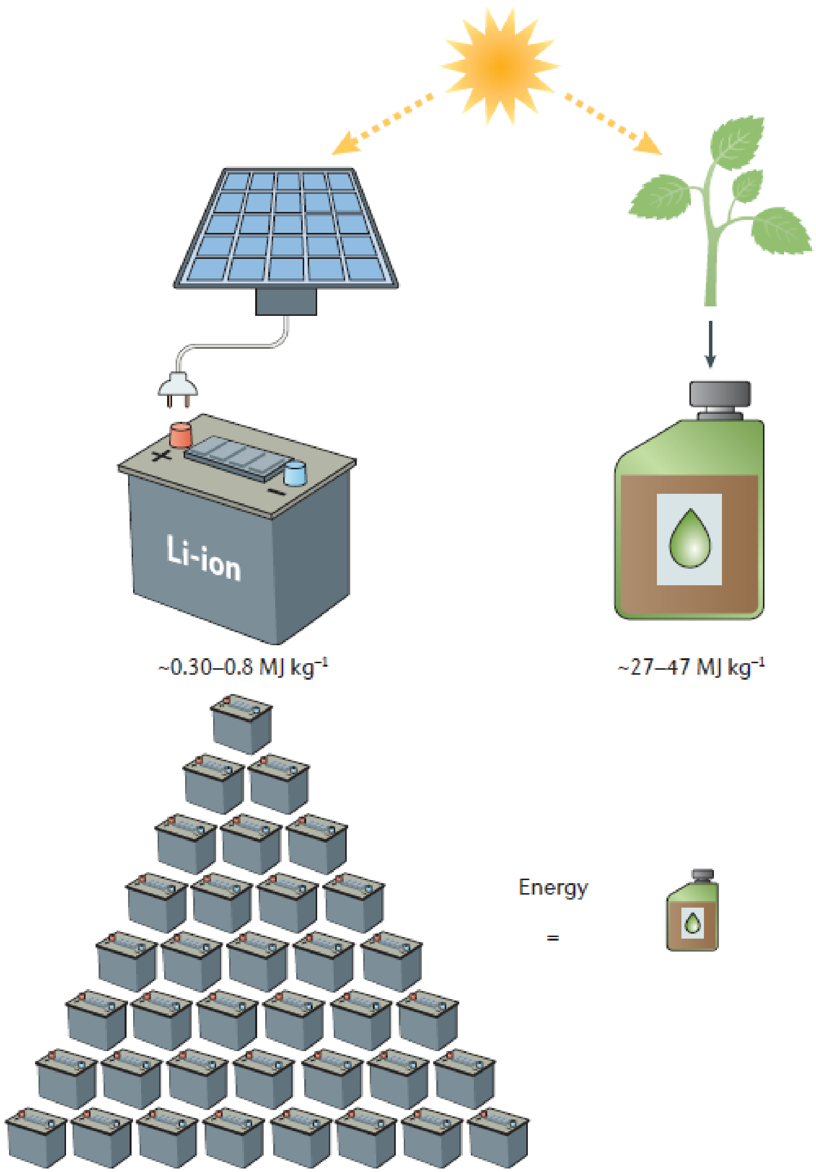
1. Biogas production, anaerobic waste water treatment
2. Bioleaching
3. Nanobiotechnology (S-layer, lipids)
4. Brine treatment (reduction of organic contamination and/or PHA production with extreme halophiles)
5. Utilization of novel (e.g. themotolerant) enzymes
6. Metabolic engineering for CO_2 utilization and/or production of specific compounds
7. Biofuel production (e.g. biomethane, biohydrogen)

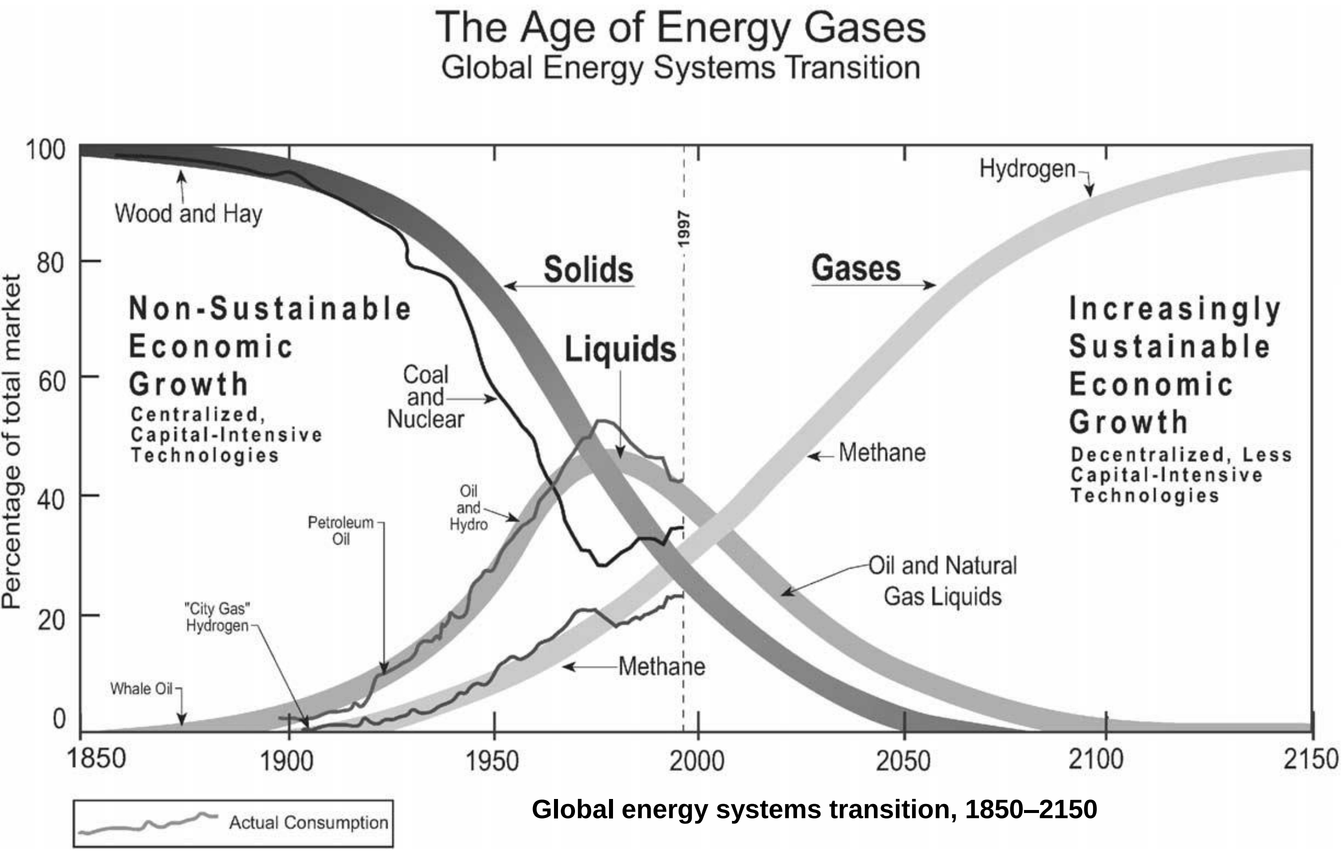
Biofuels



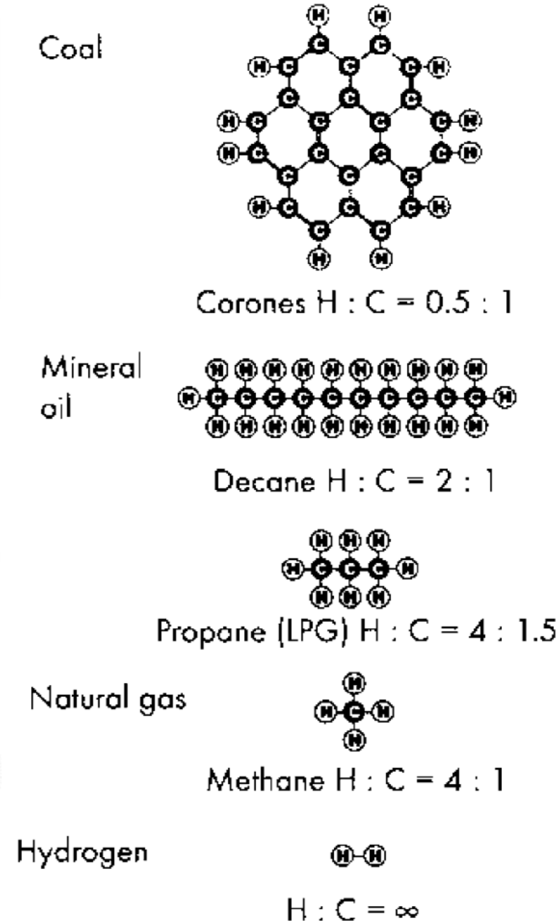
renewablegreenenergypower.com

Liao *et al.*, 2016

Biofuels: Why?



Global energy systems transition, 1850–2150

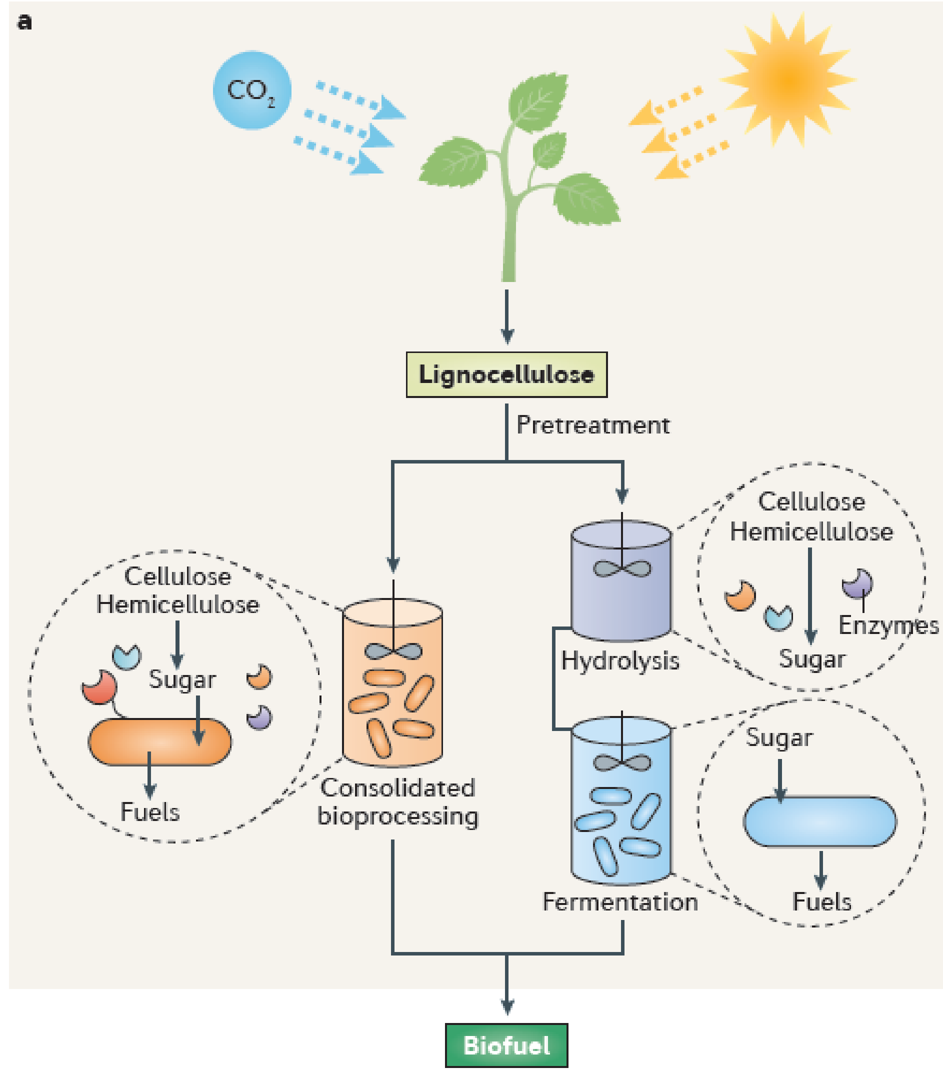


The atomic hydrogen to carbon ratio

Winter, 2000

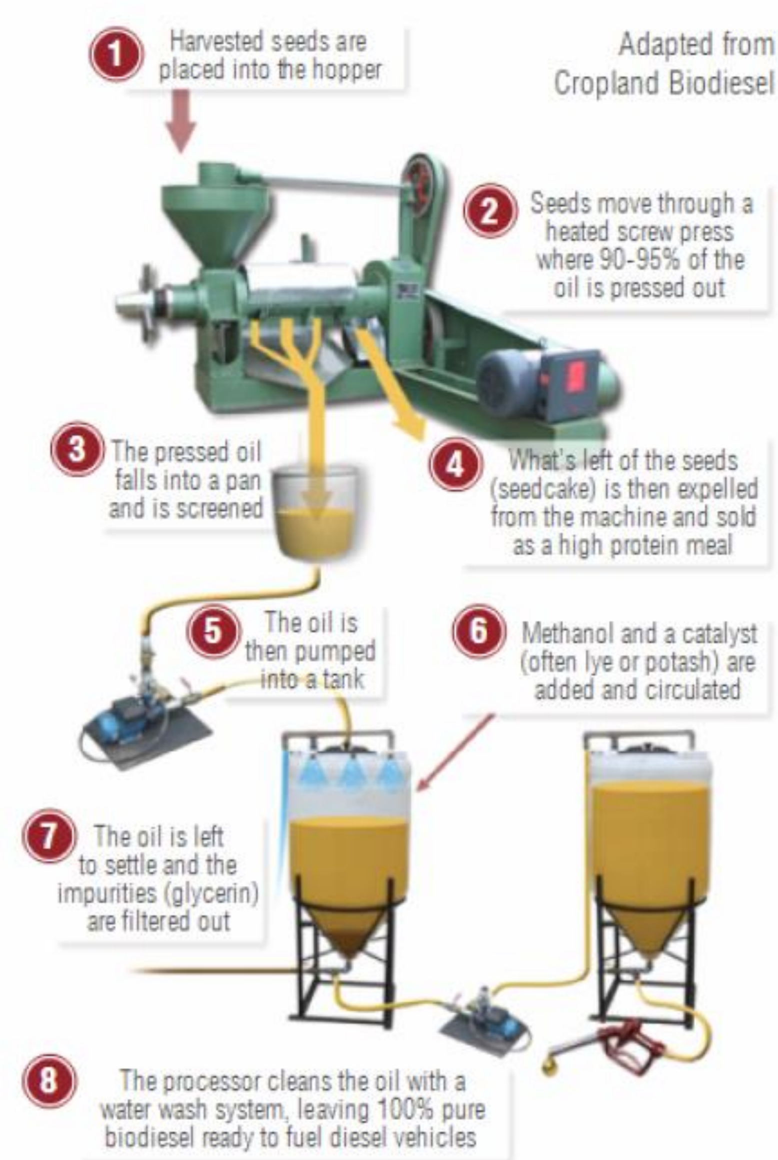
Biofuels

- 1st generation biodiesel
- 1st generation bioethanol
- 2nd generation
- 3rd generation
- 4th generation
- 5th generation



Liao *et al.*, 2016

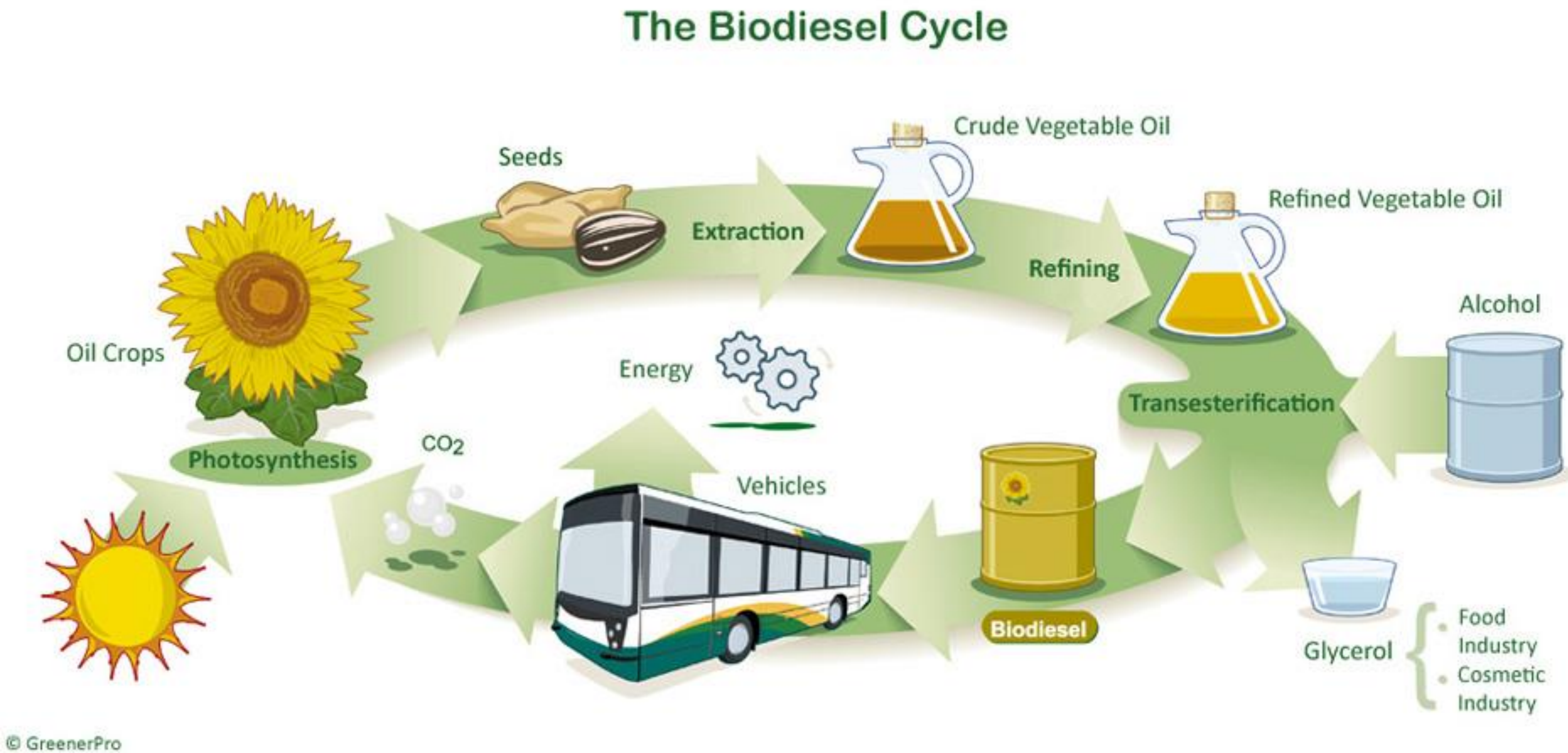
Biodiesel – 1st generation



1. Unloading
2. Pressing
3. Filtering
4. Extraction of meal
5. Pumping
6. Addition of reactants
7. Transesterification and settling
8. Washing

desmoinesregister.com &Eco Energie Etoy

Biodiesel – 1st generation



alternative-energy-news.info/technology/biofuels/biodiesel-fuel

Bioethanol – 1st generation

1. Unloading
2. Milling
3. Mashing
4. Cooking
5. Hydrolysis
6. Cooling
7. Fermentation
8. Distillation
9. Dehydration
10. Storage
11. Stillage treatment

desmoinesregister.com

Bioethanol – 1st generation

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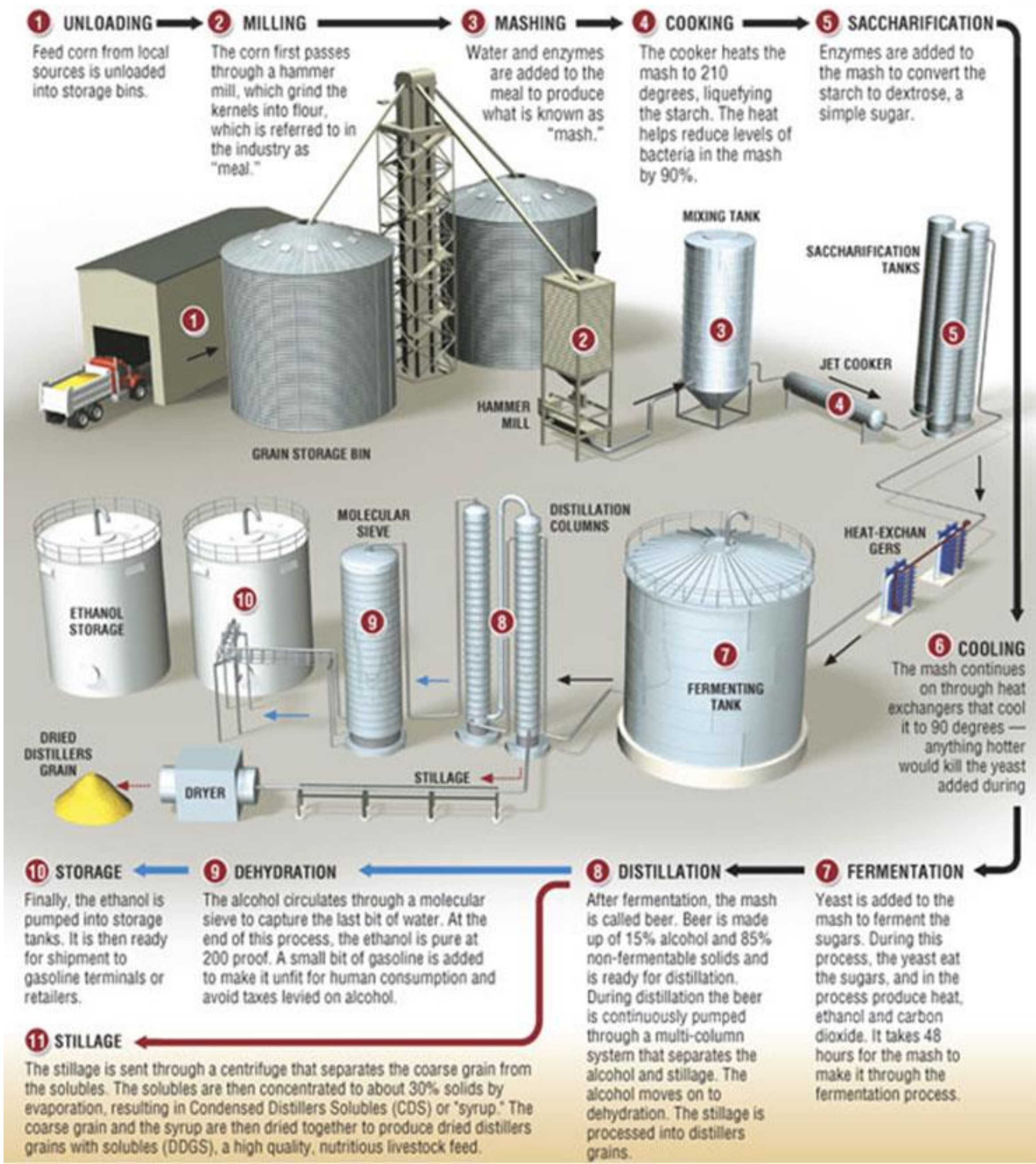
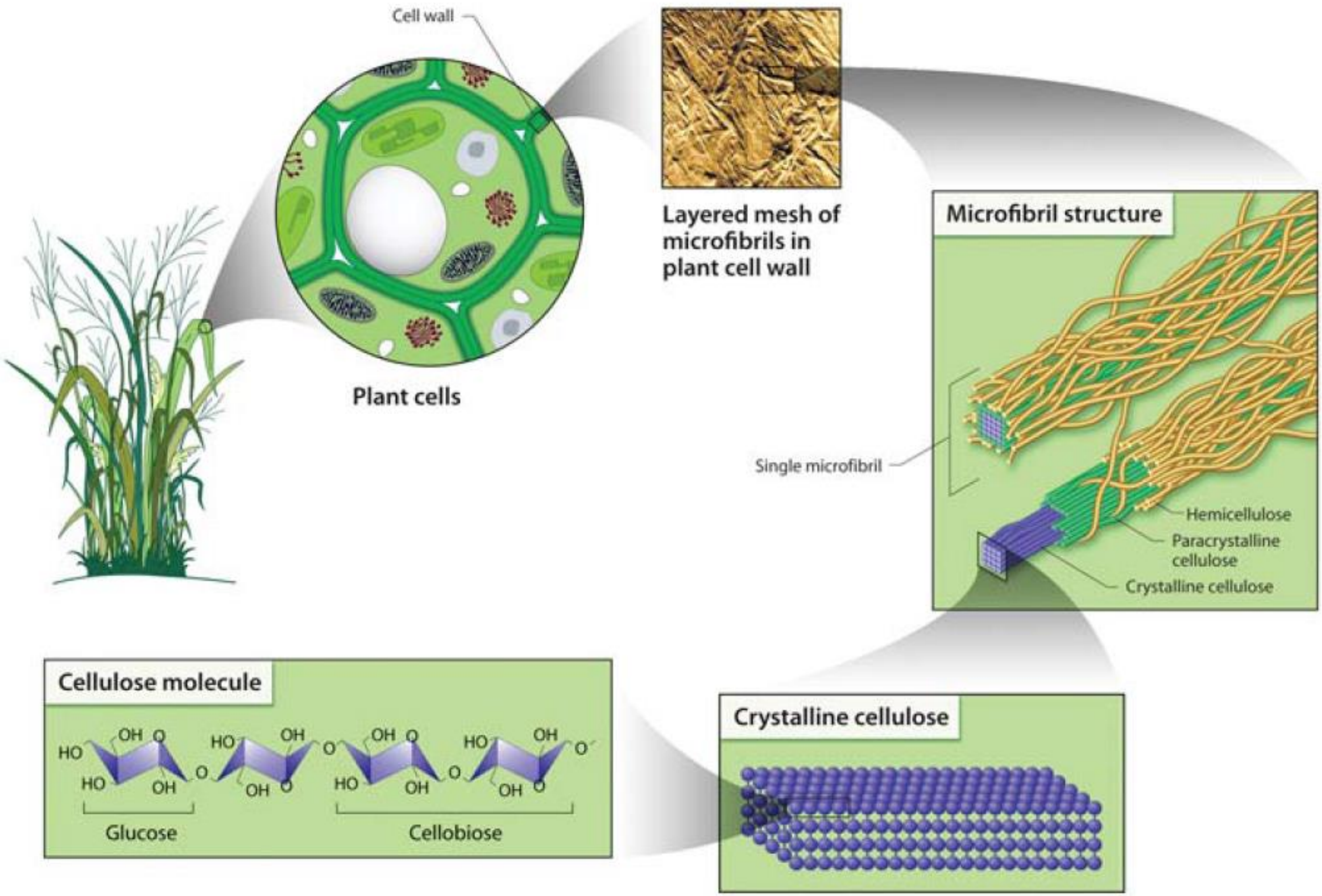


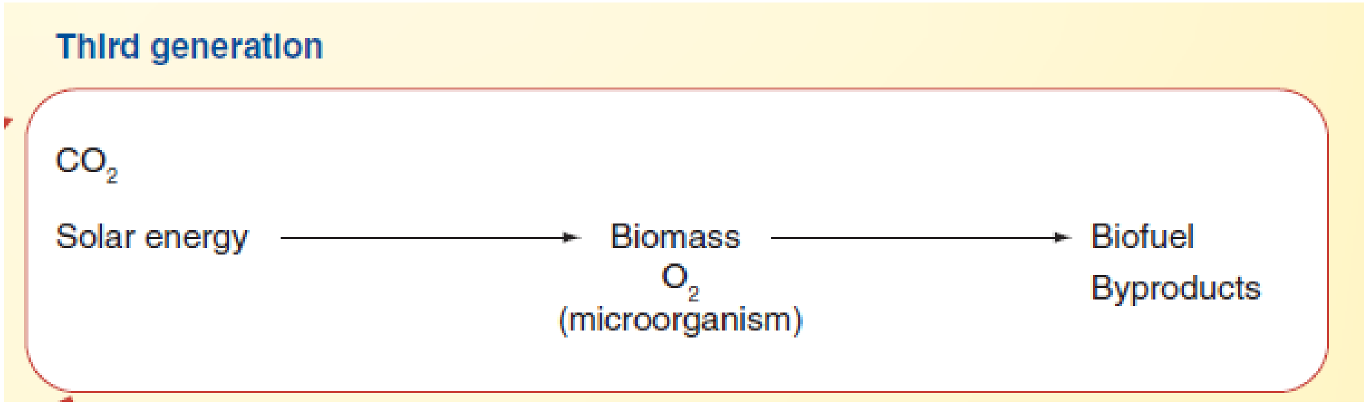
South Plains Ethanol

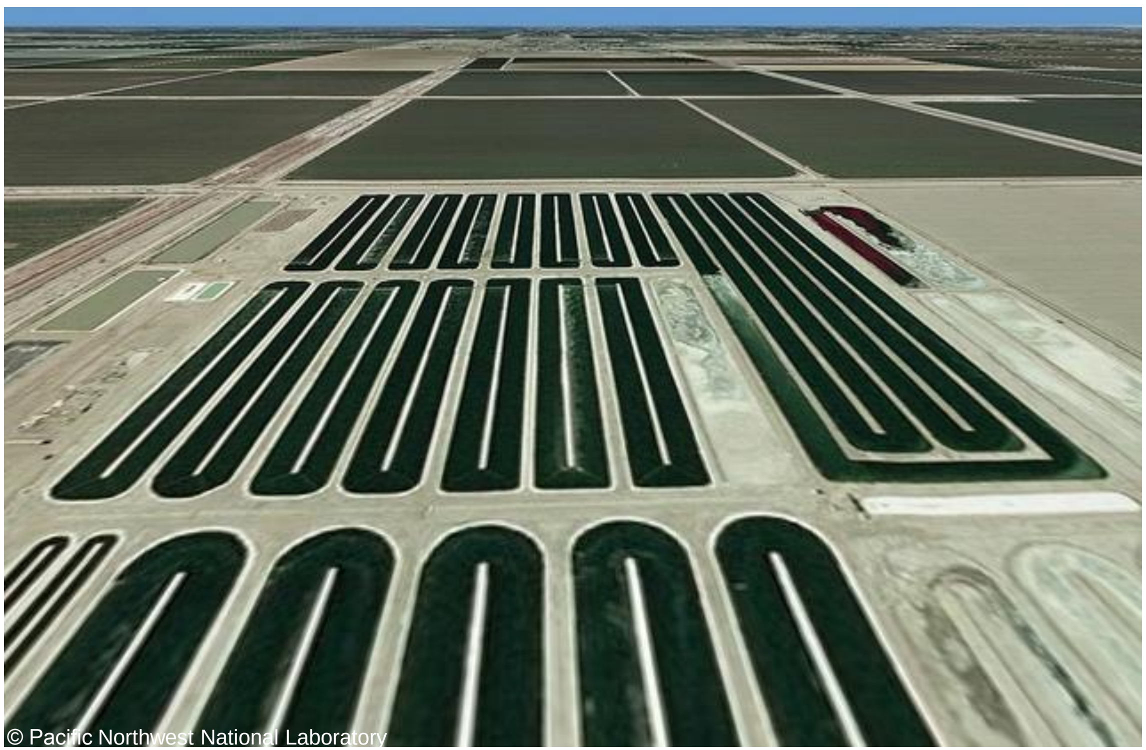
2nd biofuel generation

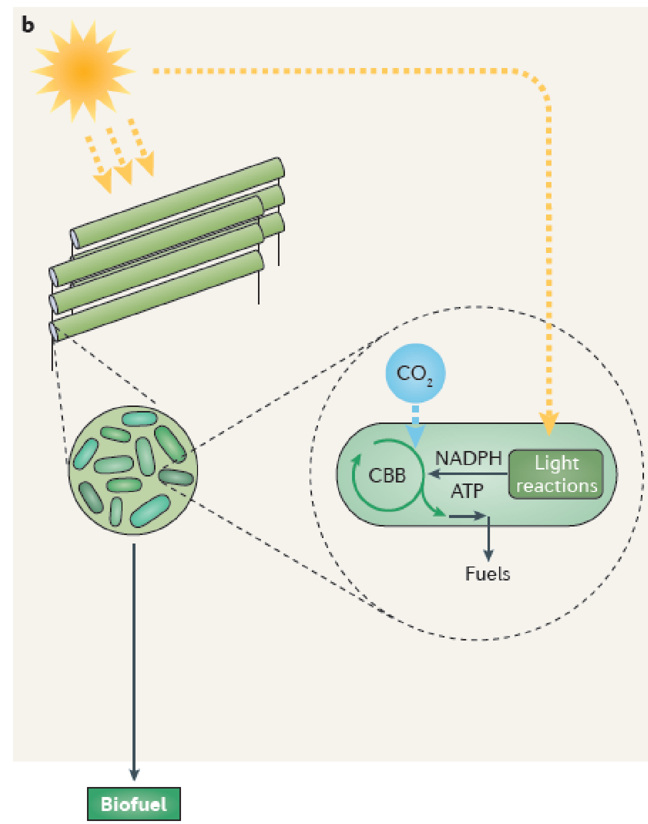


science.energy.gov.ber

3rd biofuel generation

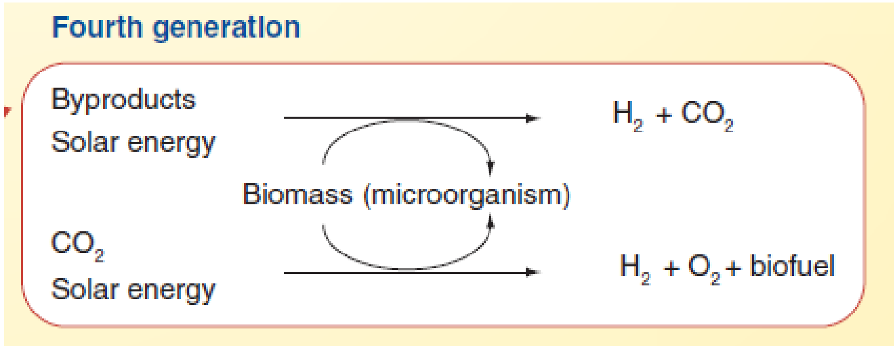


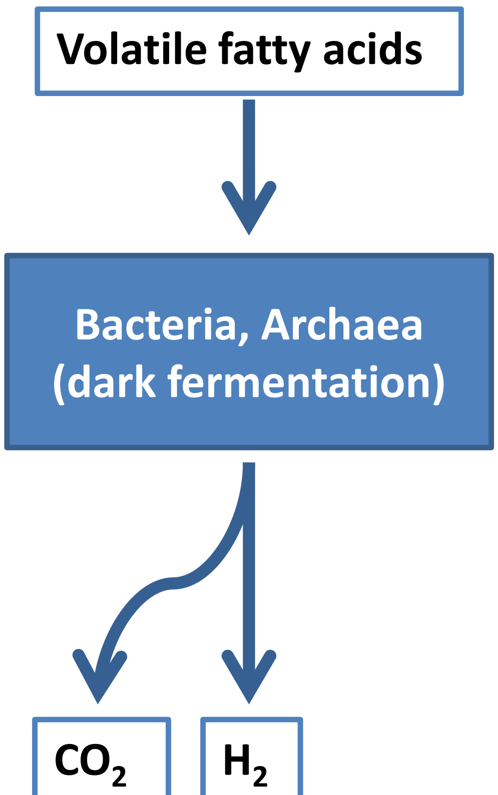


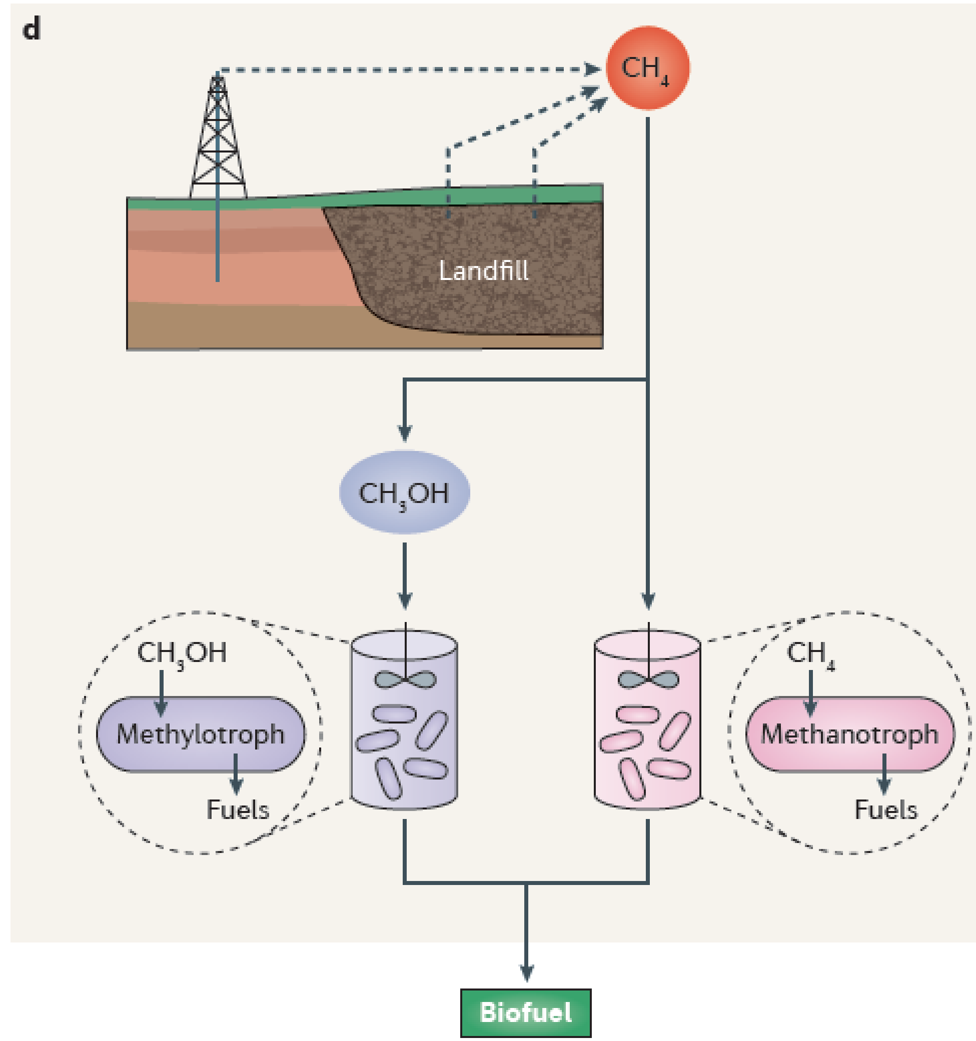


Martinez-Porqueras *et al*., 2012; Liao *et al*., 2016

4th biofuel generation

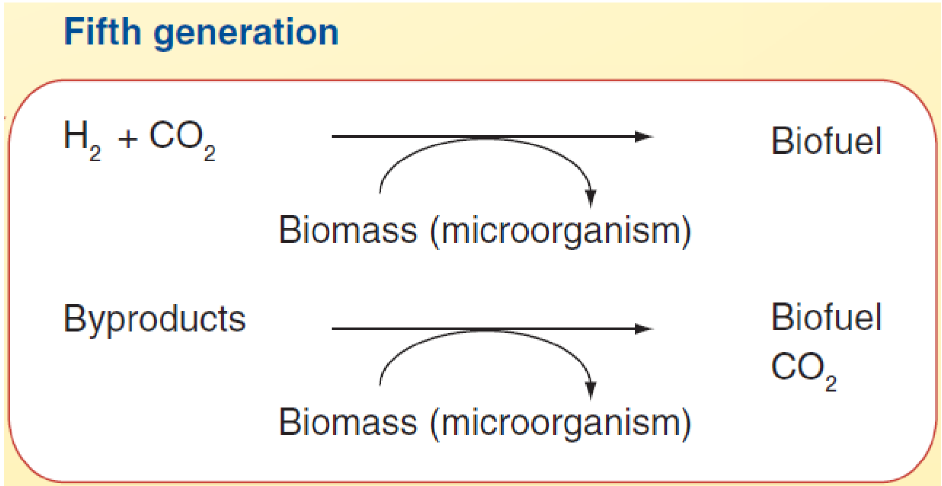


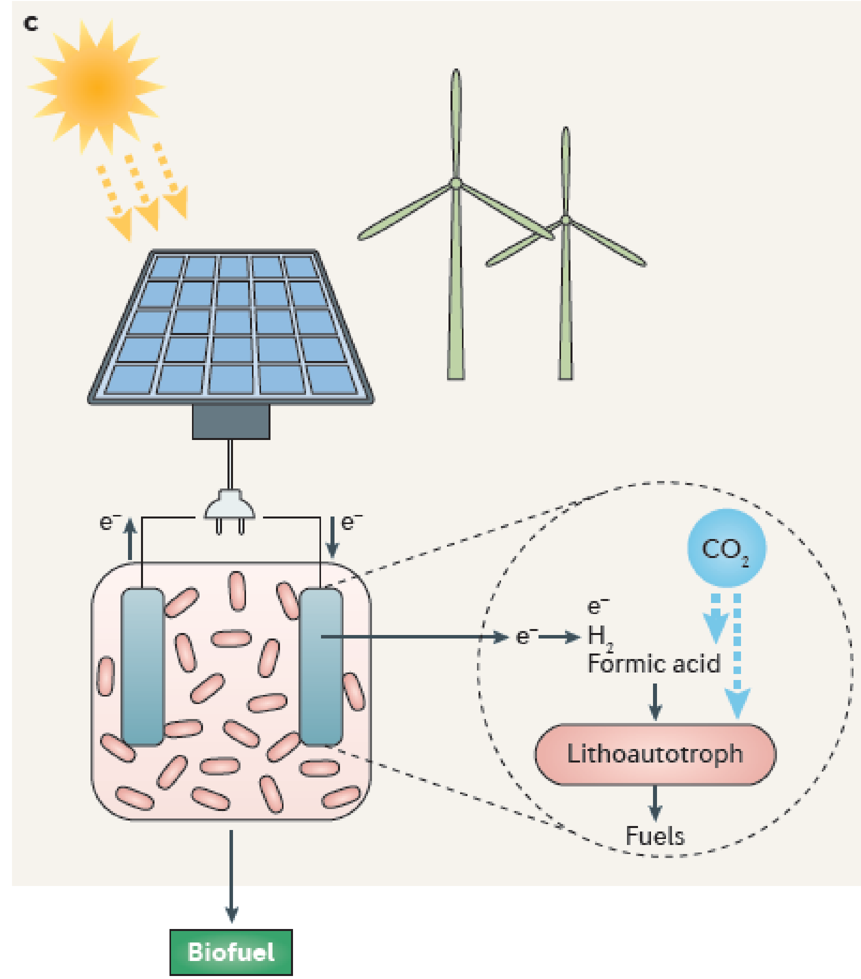


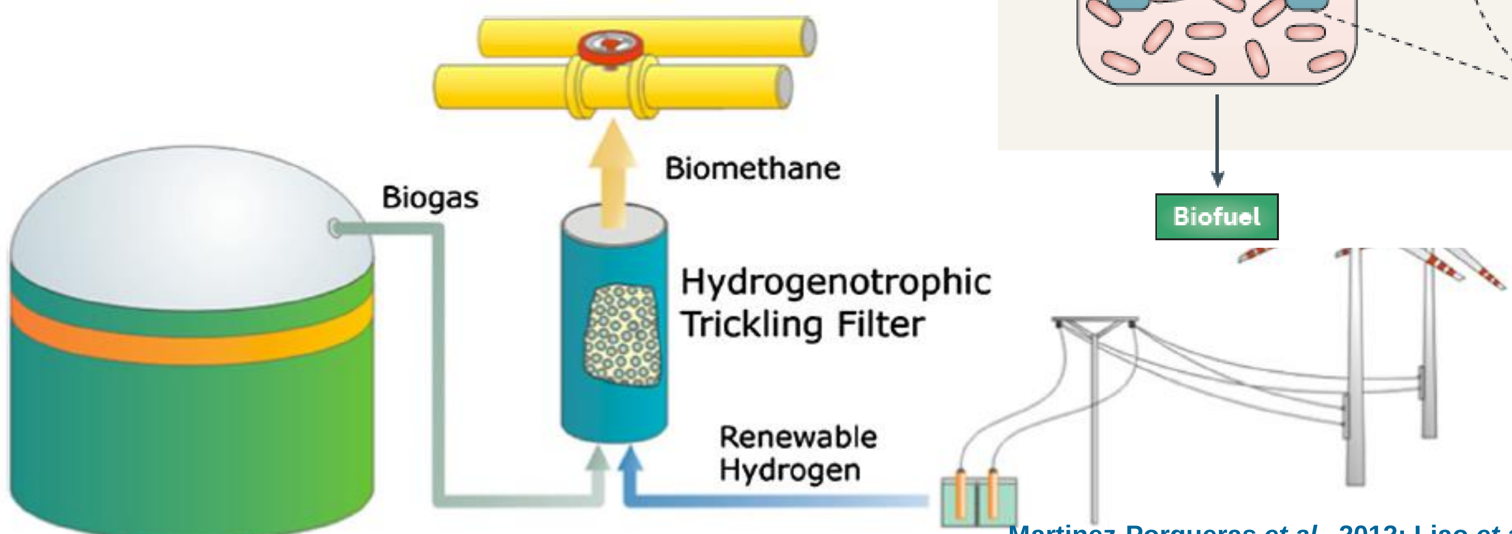


Martinez-Porqueras *et al.*, 2012; Liao *et al.*, 2016, Rittmann, unpublished

5th biofuel generation

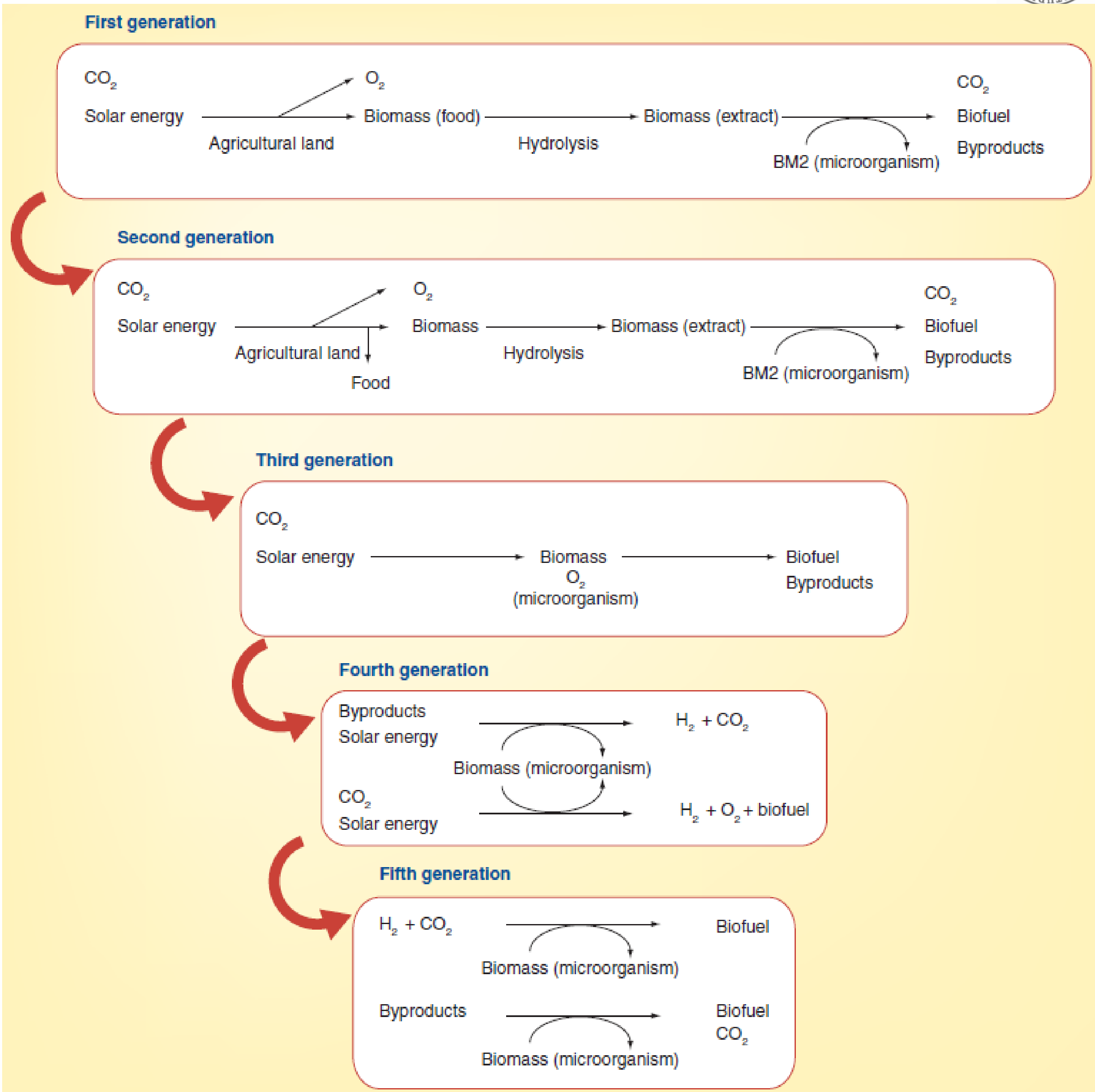






Martinez-Porqueras *et al*., 2012; Liao *et al*., 2016; Rachbauer et al., 2017

Summary biofuels



Martinez-Porqueras *et al.*, 2012

Summary biofuels

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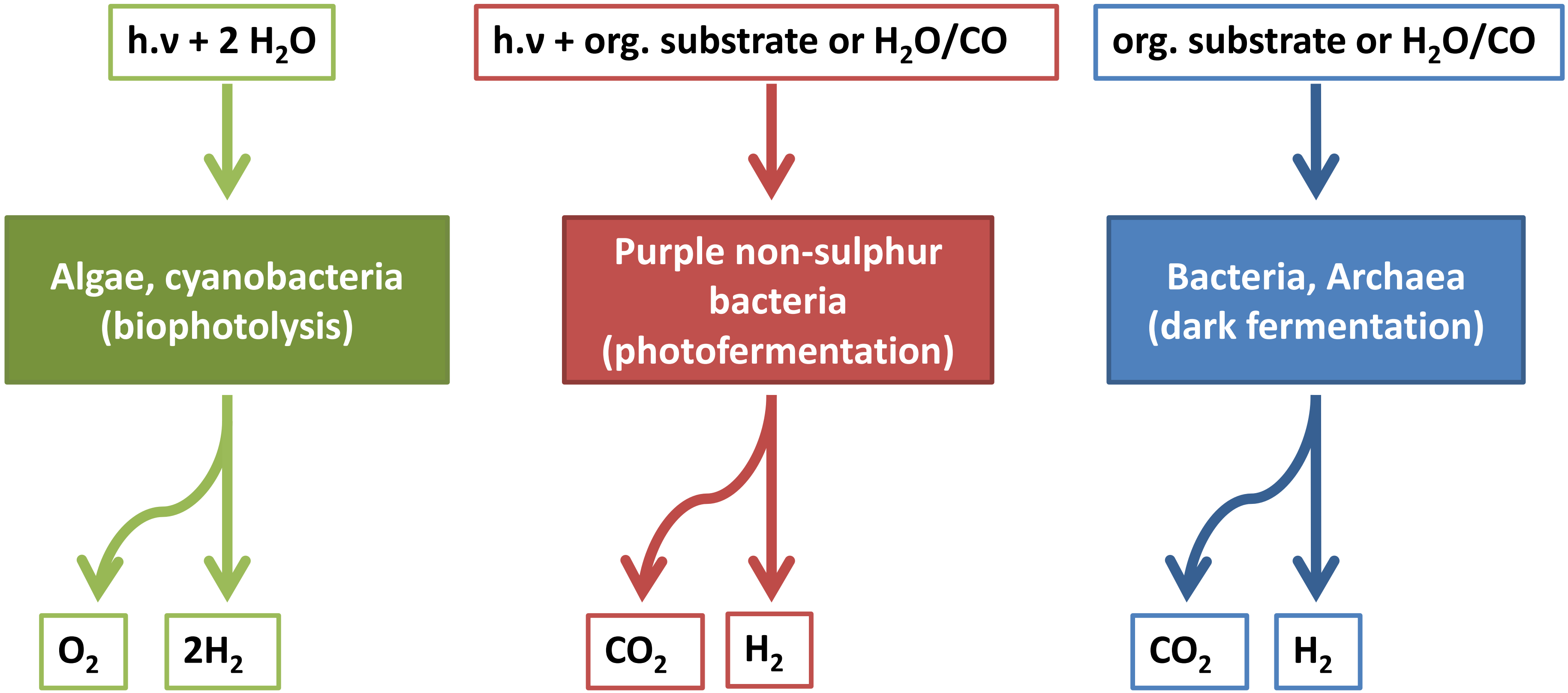
	First generation	Second generation	Third generation	Fourth generation	Fifth generation
Examples	Ethanol/biodiesel Biogas/H_2	Bioethanol/H_2 Biodiesel/biogas	Biodiesel	H_2 Bioethanol	CH_4
Raw materials	Corn Vegetable oil	Lignocellulosic residues Organic wastes	CO_2 Algae	CO_2 Byproducts	CO_2 H_2
Technology	Fermentation by conventional yeasts Transesterification by alkali catalysts	Biochemical or thermochemical routes	Biochemical or thermochemical routes	One step biocatalysis Photofermentation	Dark fermentation
Advantages	Established technology Policy drivers Proven uses	No food for fuel Acceptable carbon balances	No food for fuel No competition with agricultural land Good carbon and energy balances Any location Additional products O_2 production	Possible CO_2 neutral process Use of wastes as feedstocks O_2 production	Consumption of CO_2 Improvement of CH_4 production in biogas plants
Disadvantages	Competition with food Increase in food prices Significant CO_2 production Increased deforestation	Competition with agricultural land CO_2 production Risky investments None established	New technology Unstable biofuel Slow production Large cultivation areas	Slow Expensive Low productivity Large cultivation areas	Laboratory scale Neutral CO_2 process only when the H_2 to CO_2 ratio is equal or higher than four

Martinez-Porqueras *et al.*, 2012

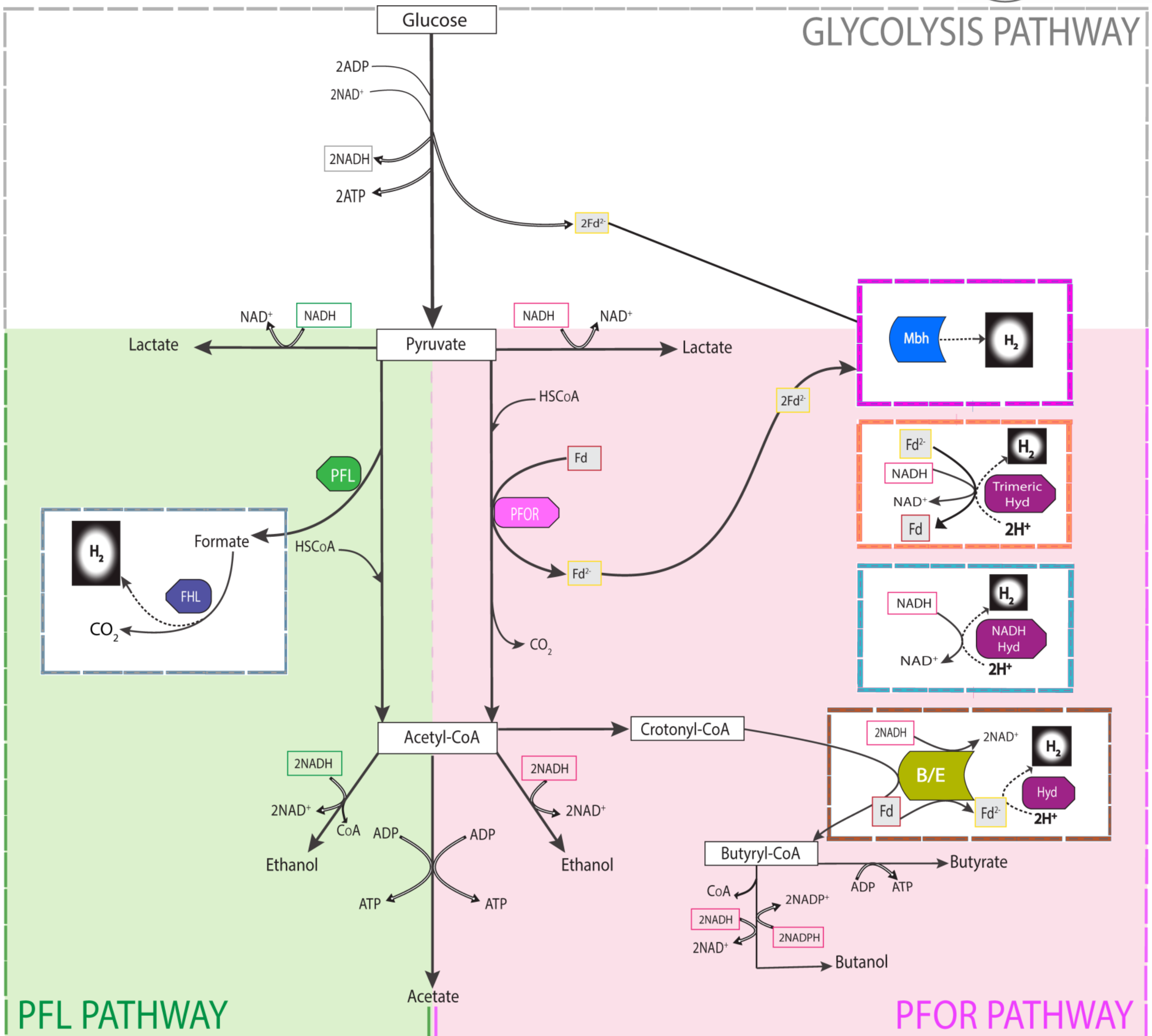
Biohydrogen production



hydrogen evolution rate (HER) of **0.1 to 0.4** mol m^{-3} h^{-1}

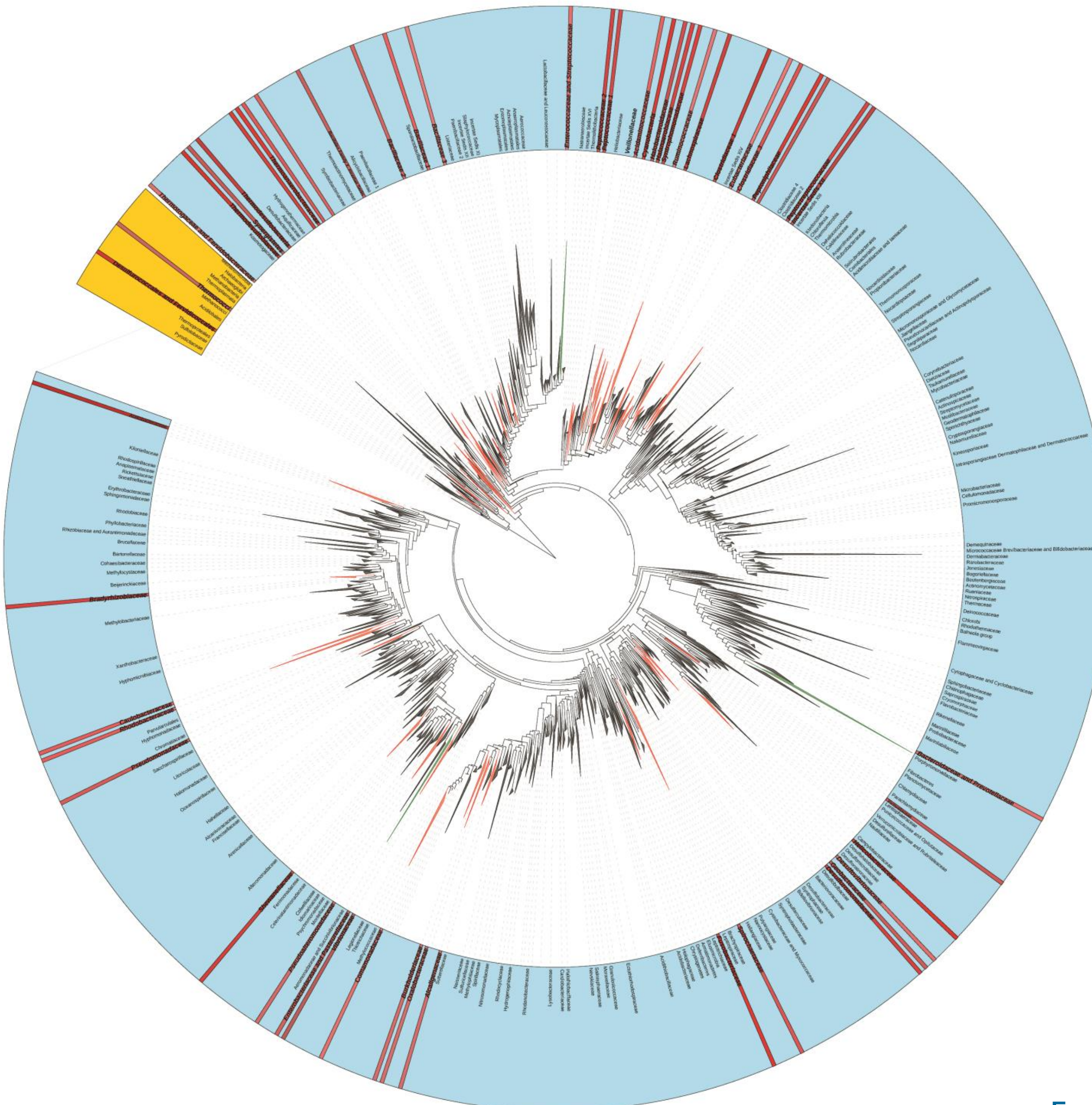
HER up to **200** mol m^{-3} h^{-1}

Dark fermentative H_2 production



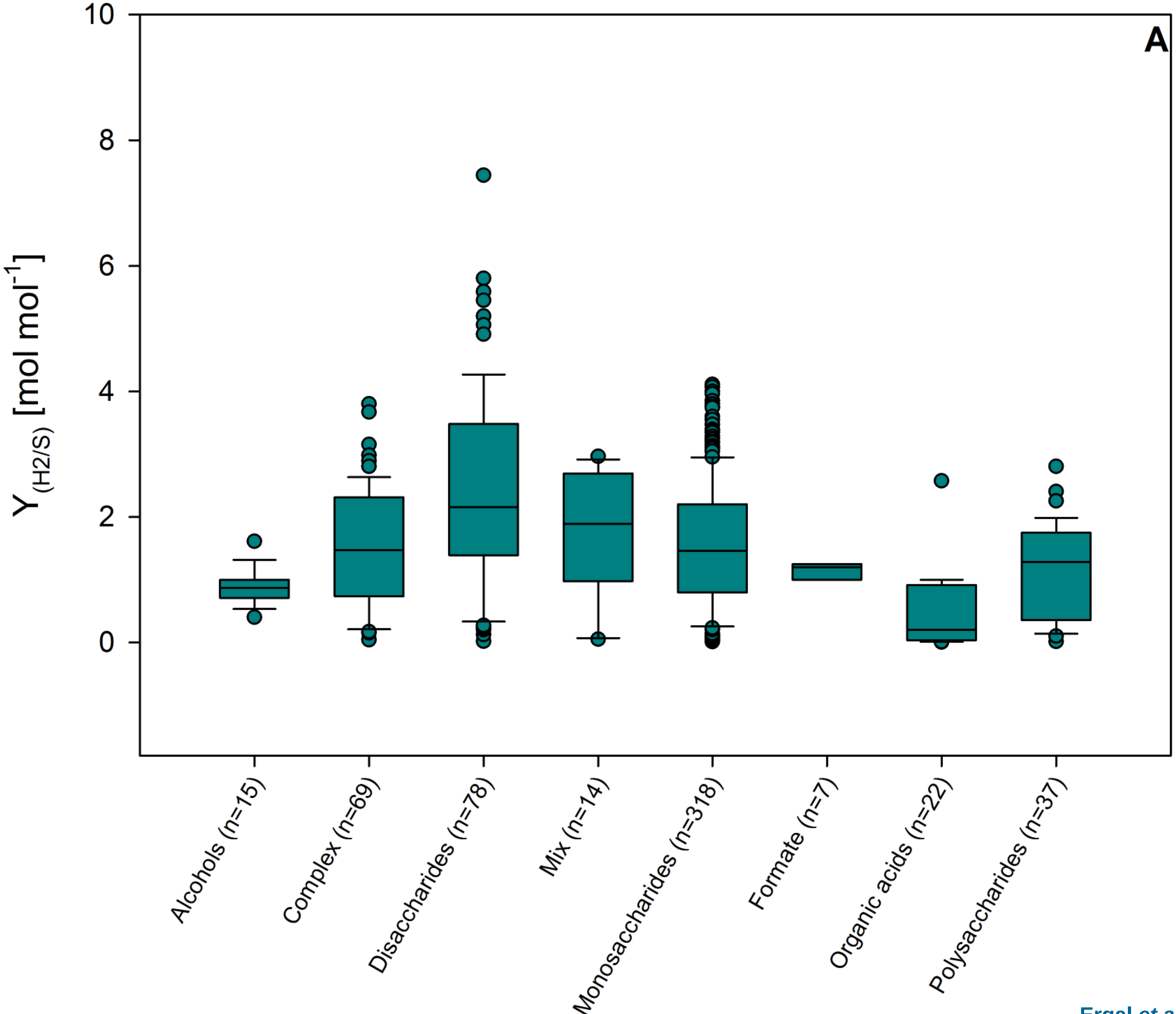
Ergal *et al*. 2018
J Biotech Adv

Dark fermentative H_2 production



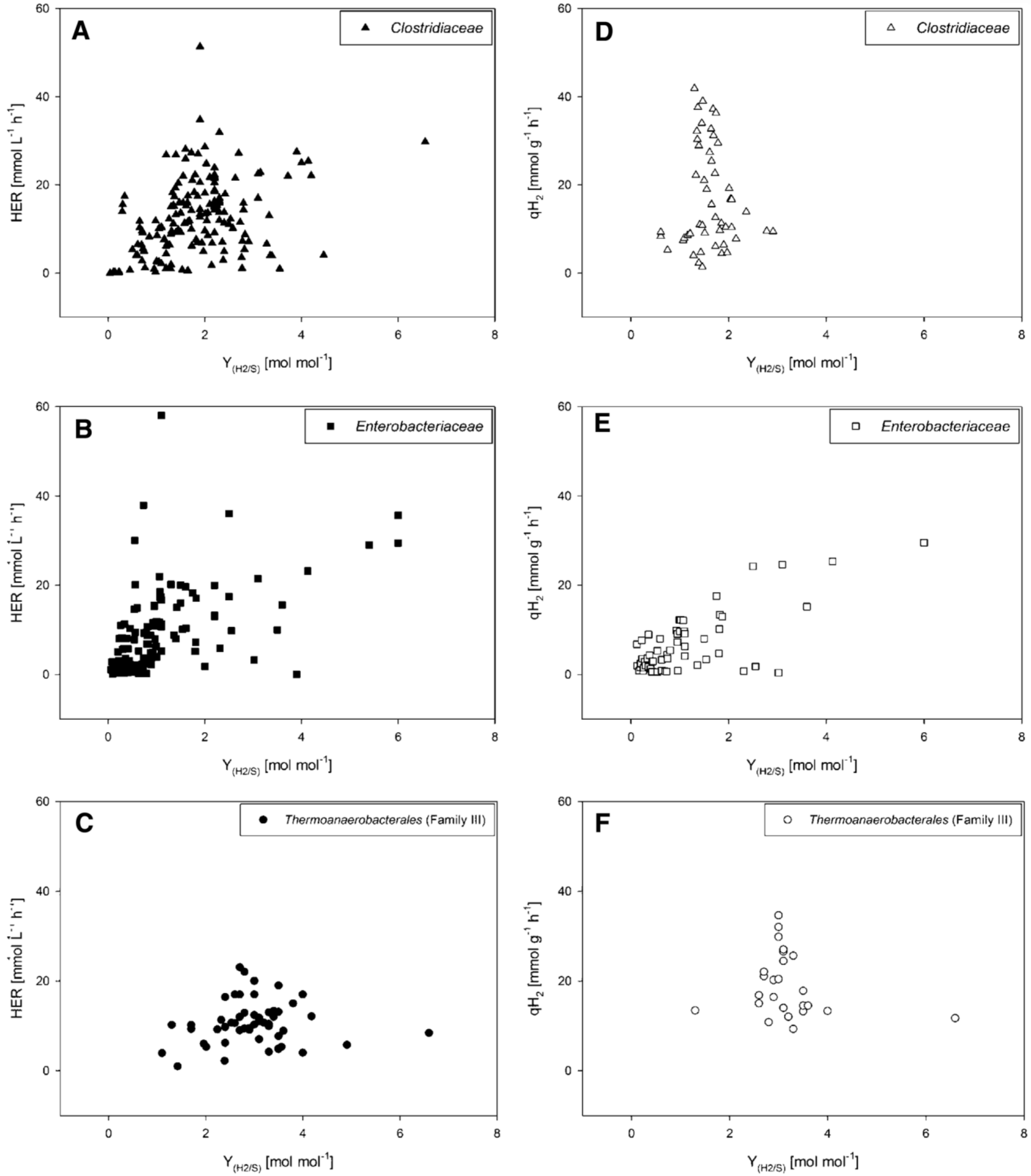
Ergal *et al*. 2018 J Biotech Adv

Dark fermentative H_2 production



Ergal *et al*. 2018 J Biotech Adv

Dark fermentative H_2 production



Rittmann *et al.*, 2012

Dark fermentative H_2 production

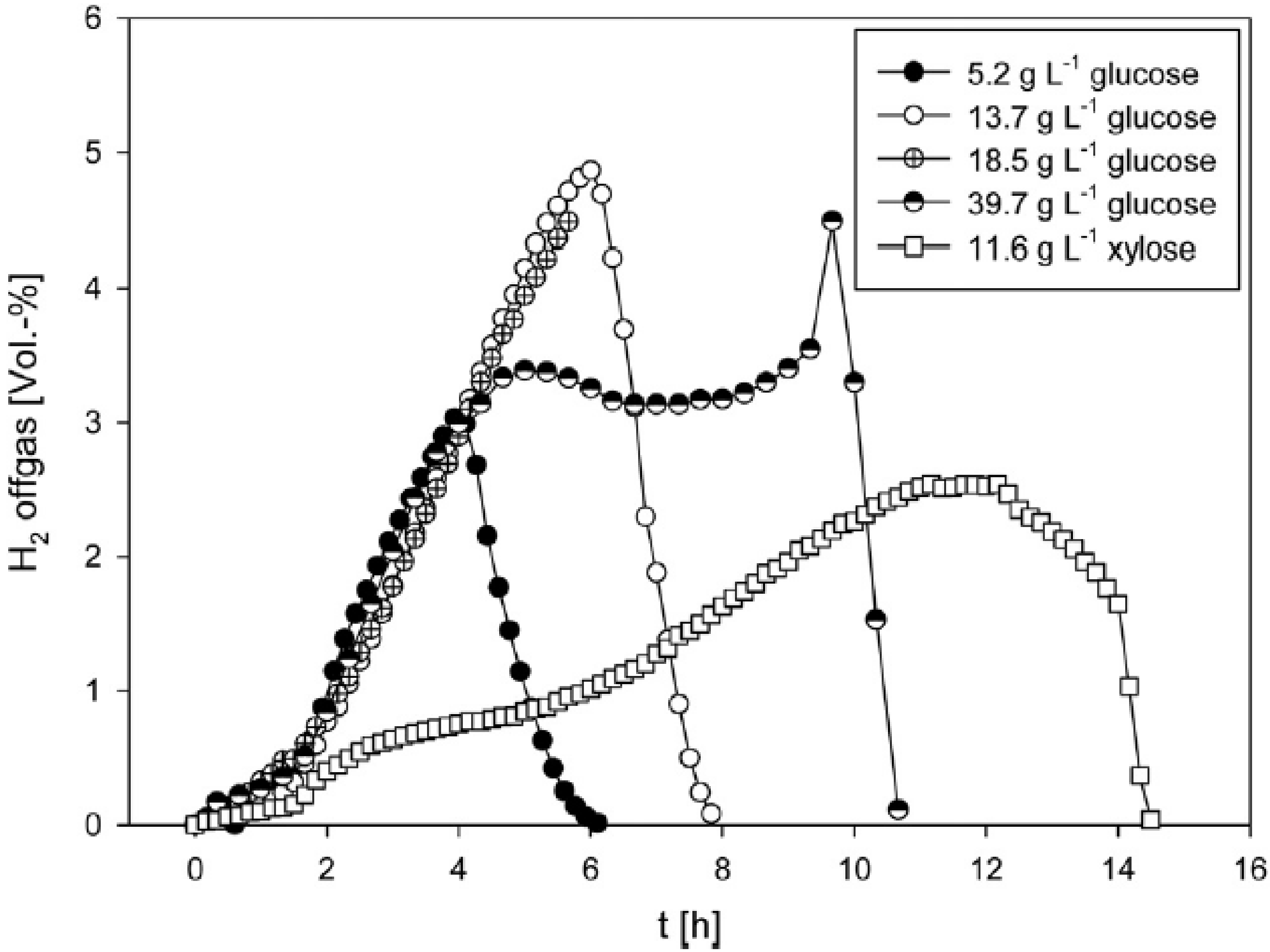


Fig. 1 – Normalized plots of H_2 production from *E. aerogenes* in repetitive batch mode on glucose or on xylose in defined medium at 30 ± 1 °C and pH = 6.80 ± 0.05, both in the presence of citrate. H_2 production signals obtained with 5.2 g/L, 13.7 g/L and 18.5 g/L glucose showed identical biohydrogen production kinetics, whereas H_2 production kinetics from 39.7 g/L glucose concentration resulted in a prominent plateau phase. Cultivation of *E. aerogenes* on 11.6 g/L citrate and xylose revealed a diauxic growth like during H_2 production, compared to the growth of *E. aerogenes* on citrate and glucose. These H_2 production curves clearly show that K_s-value for the uptake of xylose is much higher than the K_s-value for the uptake of glucose.

Martinez-Porqueras *et al.*, 2013

Dark fermentative H_2 production

Table 1 – Product yields and specific hydrogen productivities at the maximum hydrogen evolution rates in repetitive batch fermentations of *E. aerogenes* on glucose on defined medium at 30 ± 1 °C and pH = 6.80 ± 0.05.

$C_{s,t=0}$	HER	q_{H_2}	μ	$Y_{(H_2/CO_2)}$	$Y_{(H_2/s)}$
[g/L]	[mmol/L/h]	[mmol/g/h]	[h^{-1}]	[mol/C-mol]	[mol/C-mol]
5.2	29.09 ± 0.58	71.0 ± 3.55	0.57 ± 0.01	0.82 ± 0.03	0.65 ± 0.02
13.7	39.92 ± 0.80	59.1 ± 4.44	0.53 ± 0.01	0.92 ± 0.04	0.55 ± 0.02
39.7	25.39 ± 0.51	54.6 ± 4.09	0.58 ± 0.01	0.62 ± 0.02	0.35 ± 0.01

Table 2 – Physiological key parameters at the maximum hydrogen evolution rate in repetitive batch fermentations of *C. saccharolyticus* on xylose (5 g/L) on complex or defined medium at 70.0 ± 0.5 °C and pH = 6.50 ± 0.05.

		ΔC_s	HER	q_{H_2}	$Y_{(H_2/CO_2)}$	$Y_{(H_2/s)}$	$Y_{(CO_2/s)}$	$Y_{(Ac/s)}$	$Y_{(Lact/s)}$	$Y_{(x/s)}$	C-balance
		[g/L]	[mmol/L/h]	[mmol/g/h]	[mol/C-mol]	[mol/C-mol]	[C-mol/C-mol]	[C-mol/C-mol]	[C-mol/C-mol]	[C-mol/C-mol]	[C-mol]
Medium 2	YE + Trypticase	3.39 ± 0.05	3.39 ± 0.07	8.39 ± 0.63	1.48 ± 0.06	0.48 ± 0.02	0.32 ± 0.01	0.52 ± 0.02	0.01 ± 0.0	0.13 ± 0.01	0.97 ± 0.04
Medium 3	YE + Vitamins	2.84 ± 0.04	2.84 ± 0.06	8.03 ± 0.60	1.40 ± 0.06	0.44 ± 0.02	0.31 ± 0.01	0.57 ± 0.02	0.02 ± 0.0	0.16 ± 0.01	1.05 ± 0.04
Medium 4	Vitamins	2.06 ± 0.03	2.01 ± 0.04	8.29 ± 0.62	1.44 ± 0.06	0.57 ± .0.02	0.40 ± 0.01	0.70 ± 0.02	0.00 ± 0.0	0.21 ± 0.01	1.25 ± 0.05

Martinez-Porqueras *et al.*, 2013

Dark fermentative H_2 production

Table 3 – Product yields and volumetric and specific hydrogen productivities in continuous cultures of *E .aerogenes* on glucose (18.5 g/L) on defined medium at 30 ± 1 °C and different pH values.

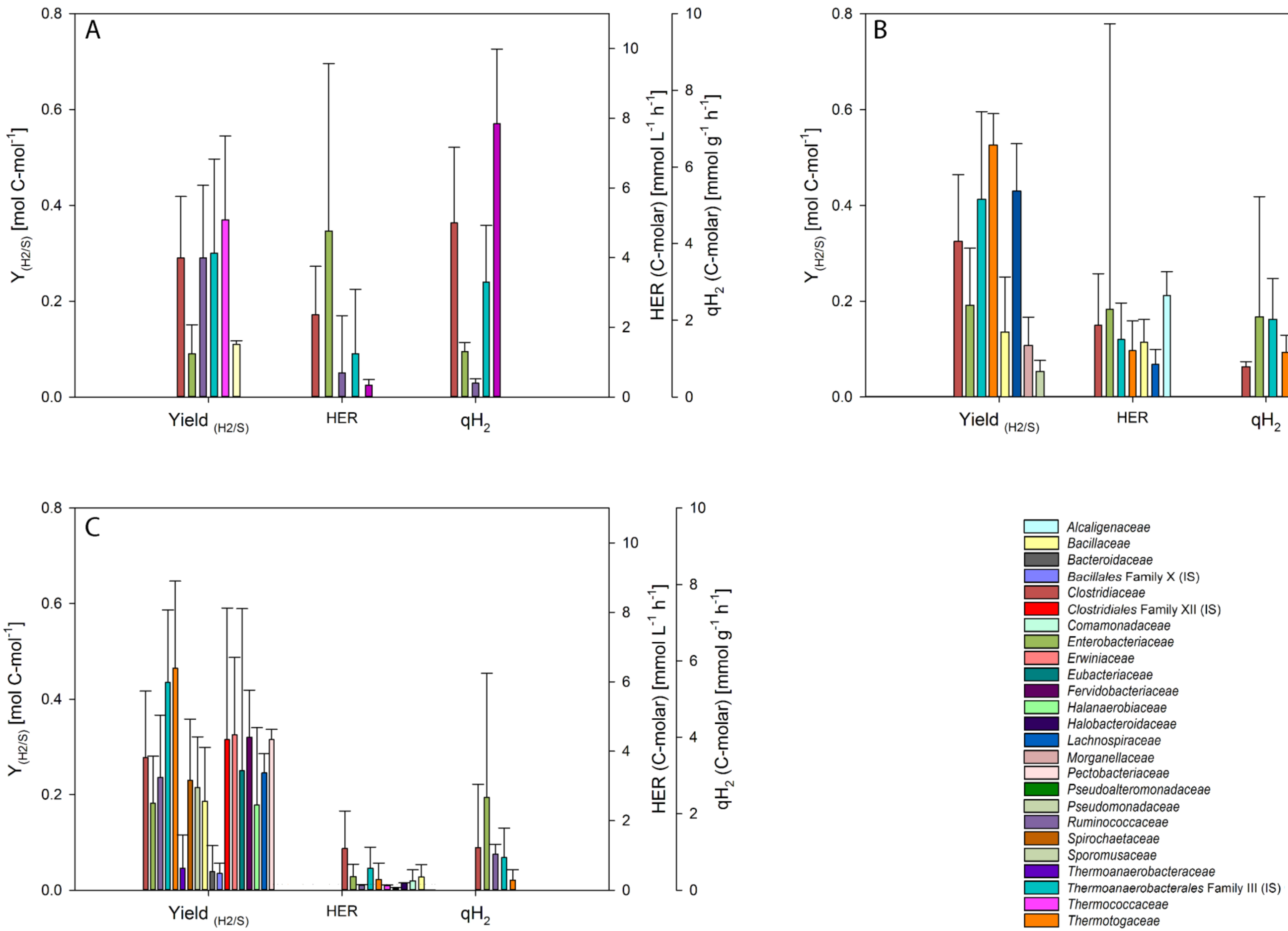
D $[h^{-1}]$	pH [–]	HER [mmol/L/h]	q_{H_2} [mmol/g/h]	$Y_{(H_2/CO_2)}$ [mol/C-mol]	$Y_{(H_2/s)}$ [mol/C-mol]	$Y_{(Ac/s)}$ [C-mol/C-mol]	$Y_{(EtOH/s)}$ [C-mol/C-mol]	$Y_{(x/s)}$ [C-mol/C-mol]
0.13	6.81	11.72 ± 0.23	5.30 ± 0.40	0.72 ± 0.03	0.15 ± 0.01	0.30 ± 0.01	0.19 ± 0.00	0.16 ± 0.01
0.25	6.81	19.82 ± 0.40	9.01 ± 0.68	0.61 ± 0.02	0.13 ± 0.00	0.28 ± 0.00	0.16 ± 0.00	0.15 ± 0.01
0.25	6.60	16.53 ± 0.33	7.45 ± 0.56	0.48 ± 0.02	0.11 ± 0.00	0.27 ± 0.00	0.17 ± 0.00	0.15 ± 0.01
0.25	6.40	13.12 ± 0.26	5.99 ± 0.45	0.38 ± 0.02	0.09 ± 0.00	0.22 ± 0.00	0.16 ± 0.00	0.14 ± 0.01

Table 4 – Physiological key parameters in continuous cultures of *C. saccharolyticus* on glucose (4.5 g/L) on non defined medium at 70.0 ± 0.7 °C and pH = 6.70 ± 0.05.

D $[h^{-1}]$	x [g/L]	HER [mmol/L/h]	q_{H_2} [mmol/g/h]	Y_{H_2/CO_2} [C-mol/C-mol]	$Y_{H_2/s}$ [mol/C-mol]	Y_{CO_2} [C-mol/C-mol]	$Y_{acet/s}$ [C-mol/C-mol]	$Y_{lact/s}$ [C-mol/C-mol]	$Y_{x/s}$ [C-mol/C-mol]	C-balance [C-mol]
0.05	0.52 ± 0.02	2.49 ± 0.05	4.82 ± 0.24	1.37 ± 0.05	0.34 ± 0.01	0.25 ± 0.01	0.55 ± 0.02	0.06 ± 0.00	0.14 ± 0.01	1.00 ± 0.04
0.1	0.86 ± 0.03	4.26 ± 0.09	4.98 ± 0.25	1.37 ± 0.05	0.29 ± 0.01	0.21 ± 0.01	0.46 ± 0.01	0.07 ± 0.00	0.24 ± 0.02	0.98 ± 0.04
0.15	0.77 ± 0.02	6.79 ± 0.014	8.81 ± 0.44	1.35 ± 0.05	0.31 ± 0.01	0.23 ± 0.01	0.46 ± 0.01	0.07 ± 0.00	0.21 ± 0.01	0.97 ± 0.04

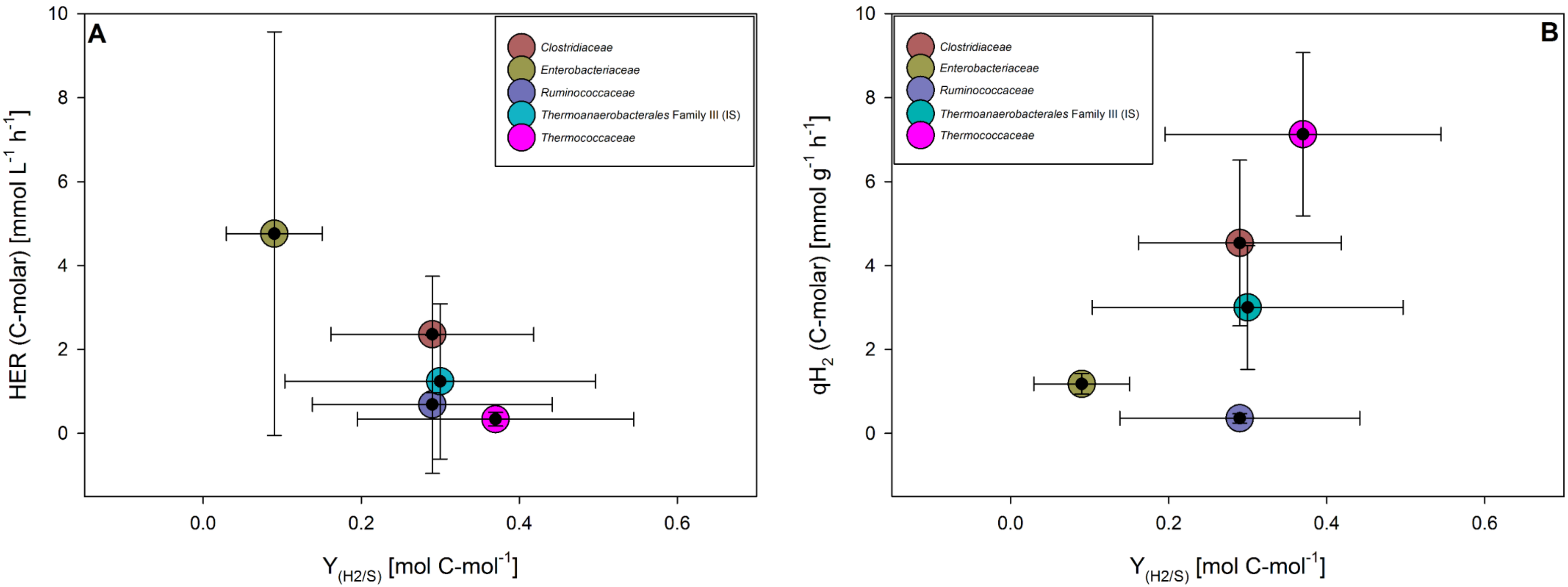
Martinez-Porqueras *et al.*, 2013

Dark fermentative H_2 production



Ergal *et al*. 2018 J Biotech Adv

Dark fermentative H_2 production



- **117 years of dark fermentative H_2 production are reviewed (results extracted from 305 papers, the data-set comprised 1732 individual data points)**
- **H_2 productivity and $Y_{(H2/S)}$ are compared on C-molar level**
- **The best substrate for H_2 production is formate**
- **Thermococcaceae spp. comprise high $Y_{(H2/S)}$ and high qH_2 in continuous culture**
- **Thermococcales are the superior organisms for H_2 production**

Ergal *et al*. 2018 J Biotech Adv

H_2 production by Thermococcus spp.

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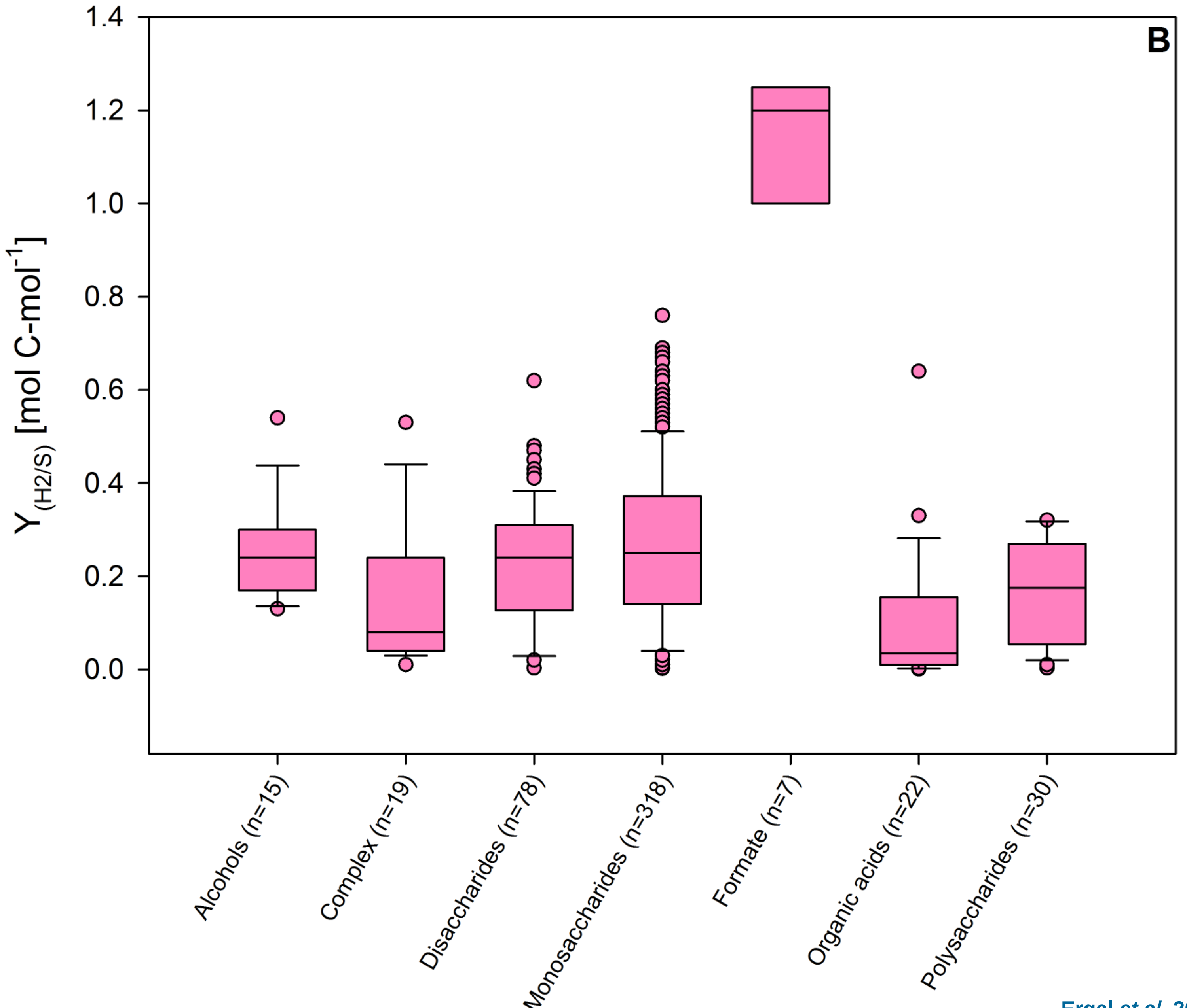
Strain	Isolation site	H_2 production	growth
T. gammatolerans	Hydrothermal chimney samples from the Guaymas basin	+	+
T. alcaliphilus	Shallow marine hydrothermal system from Vulcano	−	−
T. celer	Solfataric marine water holes from Vulcano	−	−
T. chitonophagus	Hydrothermal vent off the Mexican west coast	−	−
T. profundus	Deep-sea thermal vent from the middle Okinawa trench	−	−
T. peptonophilus	Izu-Bonin arc	−	−
T. stetteri	Marine volcanic crater fields from Kraternya cove	−	−
T. sibiricus	Oil wells in western Siberia	−	−
T. onnurineus NA1	Deep-sea hydrothermal vent in the PACMANUS field	+	+
T. barophilus Ch5	Deep-sea hydrothermal field on the Mid-Atlantic Ridge	+	+
Thermococcus sp. DS-1	Hydrothermal field on the East Pacific Rise	+	+
Thermococcus sp. DT-4	Deep-sea hot vents from the southern Pacific basin	+	+
T. litoralis Sh1B	Shallow water hot vent off the Kuril Islands	−	−
T. stetteri K1A	Shallow water hot vent off the Kuril Islands	−	−
Thermococcus sp. AM4	Deep-sea hot vent on the East Pacific Rise	−	−
Thermococcus sp. Ch1	Hydrothermal structures on the Mid-Atlantic Ridge	−	−

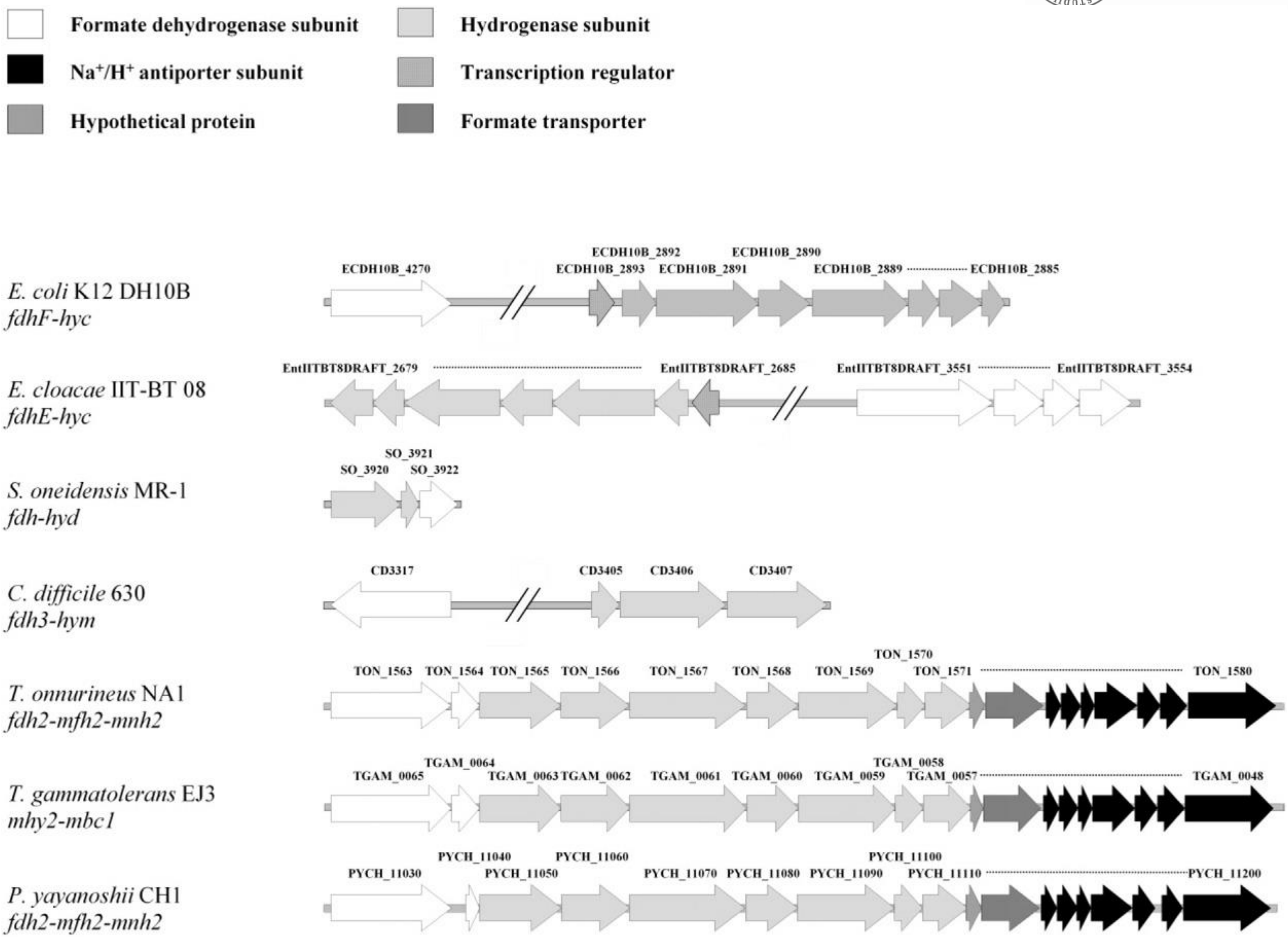
Kim *et al.*, 2010

H_2 production from formate



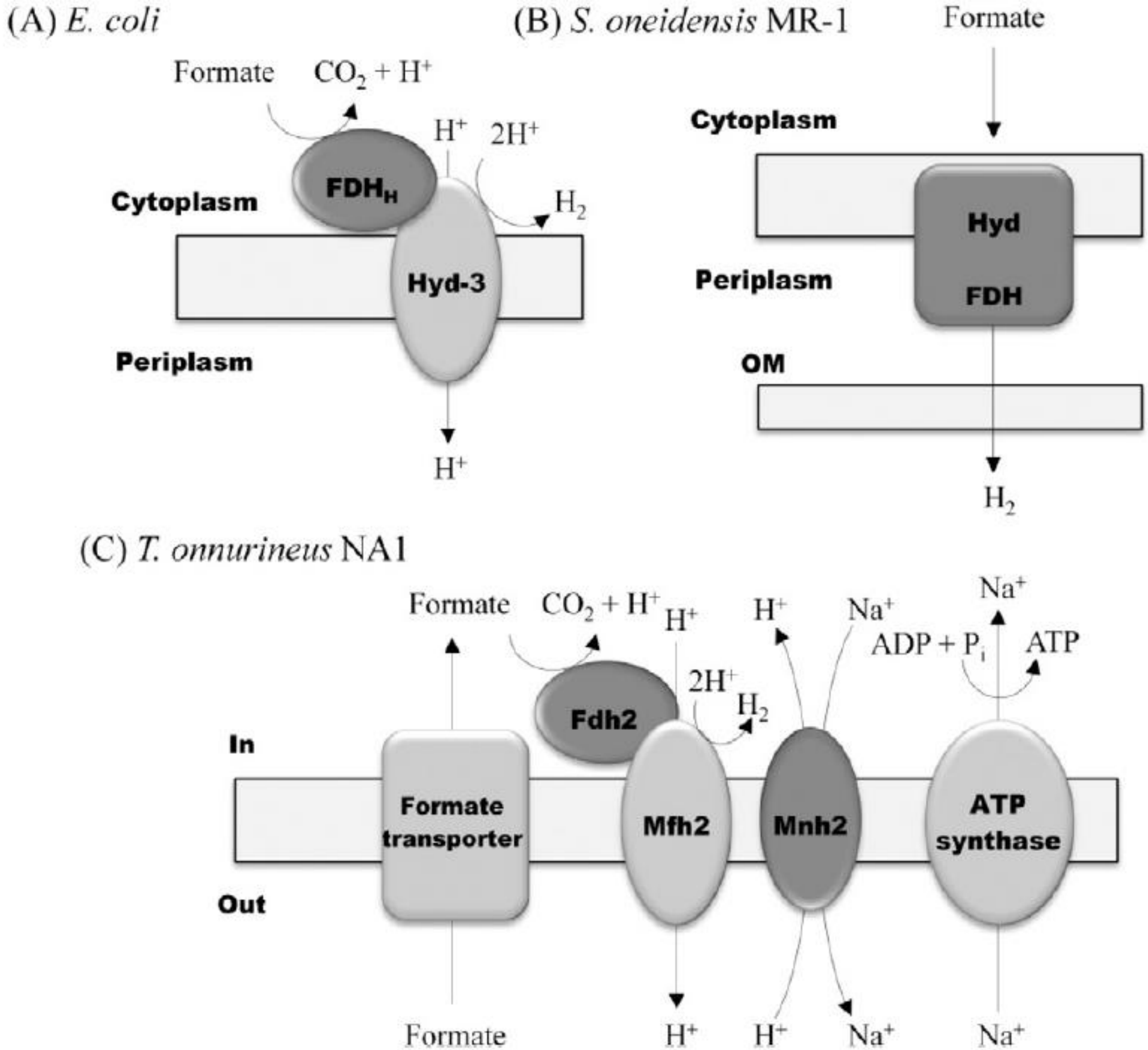
Ergal *et al*. 2018 J Biotech Adv

H_2 production from formate



Rittmann *et al*. 2015 J Biotech Adv

H_2 production from formate



Rittmann *et al*. 2015 J Biotech Adv

H_2 production from formate

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Strain	Strategy	HER [mmol L^{-1} h^{-1}]	Reference
Cupriavidus necator ATCC 17699	Immobilization of cells	5.8	Klibanov et al., 1982
Salmonella enterica	Closed batch mode	0.3	Pakes and Jollyman, 1901
Escherichia coli SH5	Fed-batch mode with immobilized cells	73.3	Seol et al., 2011
Escherichia coli SR13	hycA disruption and fhlA overexpression	11625	Yoshida et al., 2005
Clostridium butyricum IFO 3847t1	Addition of co-substrate mannitol	0.21	Heyndrickx et al., 1989
Desulfovibrio vulgaris Hildenborough	Optimization of reaction conditions	0.67	Martins and Pereira, 2013
Thermococcus onnurineus NA1	Use of high cell density	2820	Lim et al., 2012

HER: hydrogen evolution rate

➢ **Archaea perform autocatalytic hydrogen production from formate whereas bacteria only perfrom whole cell biocatalysis from formate**

Rittmann *et al*. 2012 Microb Cell Fact
Rittmann *et al*. 2015 J Biotech Adv

H_2 production from CO

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Reaction equations and their standard Gibbs free energy (G0) for several modes of carboxydotrophic growth

Metabolism		Reaction	ΔG^0 (kJ)
Fermentative			
	Hydrogenogenic	$CO + H_2O \longrightarrow CO_2 + H_2$	–20
	Methanogenic	$4\,CO + 2\,H_2O \longrightarrow CH_4 + 3\,CO_2$	–210
	Acetogenic	$4\,CO + 2\,H_2O \longrightarrow CH_3COO^- + H^+ + 2\,CO_2$	–174
	Solventogenic (ethanol)	$6\,CO + 3\,H_2O \longrightarrow C_2H_5OH + 4\,CO_2$	–224
Respiratory			
	Oxygen	$2\,CO + O_2 \longrightarrow 2\,CO_2$	–514
	Sulfate	$4\,CO + SO_4^{2-} + H^+ \longrightarrow 4\,CO_2 + HS^-$	–231

Isolated microorganisms capable of conserving energy from the water–gas shift reaction

Species	Origin	Temperature optimum (°C)	Carboxydotrophic generation time (h)	Reference
Mesophilic bacteria				
Rhodospirillum rubrum	Various environments	30	5 (dark, acetate)	Kerby et al., 1995
Rubrivivax gelatinosa	Lake sediment	34	6.7 (dark, trypticase) 10 (light, autotrophically) 1.5 (light, malate)	Uffen, 1976; Maness et al., 2005
Rhodopseudomonas palustris	Anaerobic wastewater sludge digester	30	2 (light, autotrophically)	Jung et al., 1999

Diender et al., 2015

H_2 production from CO

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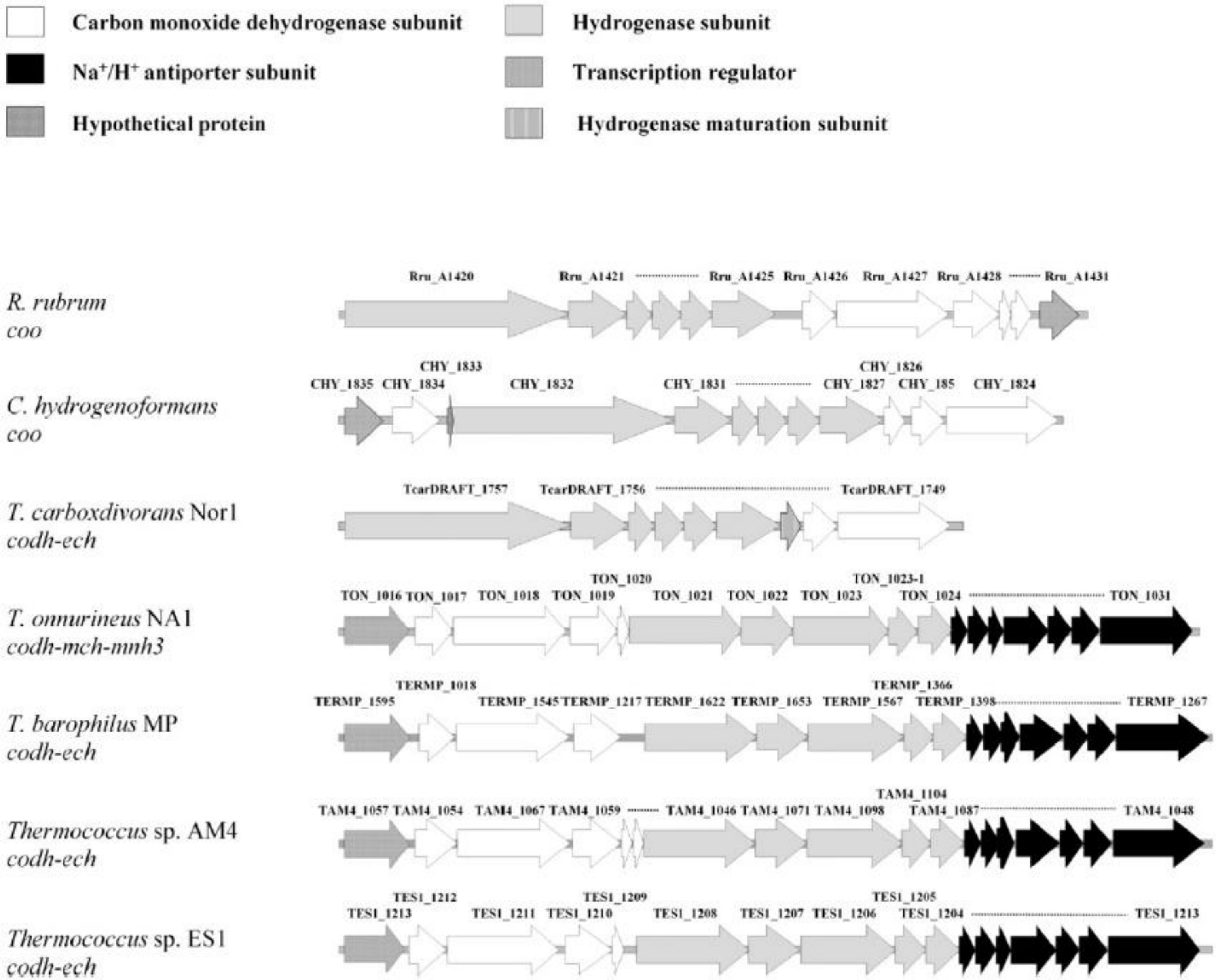
Isolated microorganisms capable of conserving energy from the water–gas shift reaction

Species	Origin	Temperature optimum (°C)	Carboxydotrophic generation time (h)	Reference
Thermophilic bacteria				
Caldanaerobacter subterraneus ssp. *pacificus*	Submarine hot vent, Okinawa Trough	70	7.1	Sokolova et al., 2001; Fardeau et al., 2004
Carboxydocella sporoproducens	Hot spring, Karymskoe Lake	60	1	Slepova et al., 2006
Carboxydocella thermoautotrophica	Terrestrial hot vent, Kamchatka Peninsula	58	1.1	Sokolova et al., 2002
Carboxydothermus hydrogenoformans	Freshwater hydrothermal spring, Kunashir Island	70	2	Svetlichny et al., 1991
Carboxydothermus islandicus	Hot spring, Hveragerdi	65	2	Novikov et al., 2011
Carboxydothermus pertinax	Volcanic acidic hot spring, Kyushu Island	65	1.5	Yoneda et al., 2012
Carboxydothermus siderophilus	Hot spring, Kamchatka Peninsula	65	9.3	Slepova et al., 2009
Dictyoglomus carboxydivorans	Hot spring, Kamchatka Peninsula	75	60	Kochetkova et al., 2011
Moorella stamsii	Digester sludge	65	N.D.	Alves et al., 2013
Thermincola carboxydiphila	Hot spring, Lake Baikal	55	1.3	Sokolova et al., 2005
Thermincola ferriacetica	Hydrothermal spring, Kunashir Island	60	N.D.	Zavarzina et al., 2007
Thermincola potens	Thermophilic microbial fuel cell	55	N.D.	Byrne-Bailey et al., 2010
Thermolithobacter carboxydivorans	Mud and water, Calcite Spring	73	1.3	Sokolova et al., 2007
Thermosinus carboxydivorans	Hot spring, Norris Basin	60	1.15	Sokolova et al., 2004a
Thermoanaerobacter thermohydrosulfuricus ssp. *carboxydovorans*	Geothermal spring, Turkey	70	N.D.	Balk et al., 2009
Desulfotomaculum carboxydivorans	Paper mill wastewater sludge	55	N.D.	Parshina et al., 2005b
Thermophilic archaea				
Thermococcus onnurineus	Deep-sea hydrothermal vent	80	5	Bae et al., 2006, 2012
Thermocuccus AM4	Hydrothermal vent	82	5	Sokolova et al., 2004b
Thermofilum carboxyditrophus	Kamchatka hot springs	90	N.D.	Kochetkova et al., 2011

Diender et al. , 2015

H_2 production from CO



Rittmann et al. , 2015

H_2 production from CO

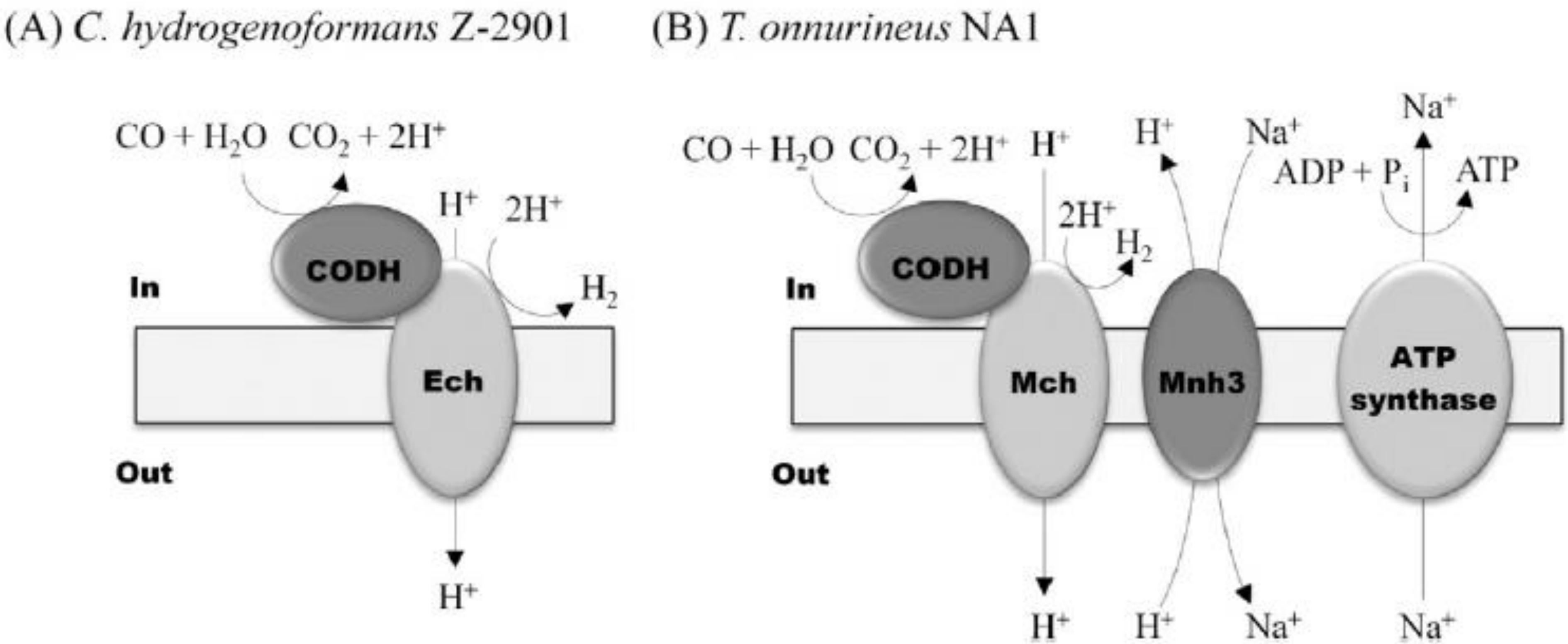


Fig. 4. Structural model of the CO-oxidizing, H2-forming enzyme complex in *Carboxydothermus hydrogenoformans* (Hedderich, 2004) (A) and *Thermococcus onnurineus* NA1 (B) and the proposed mechanism of coupling of CO oxidation with ATP synthesis.

Rittmann et al. , 2015

Archaeal biohydrogen production

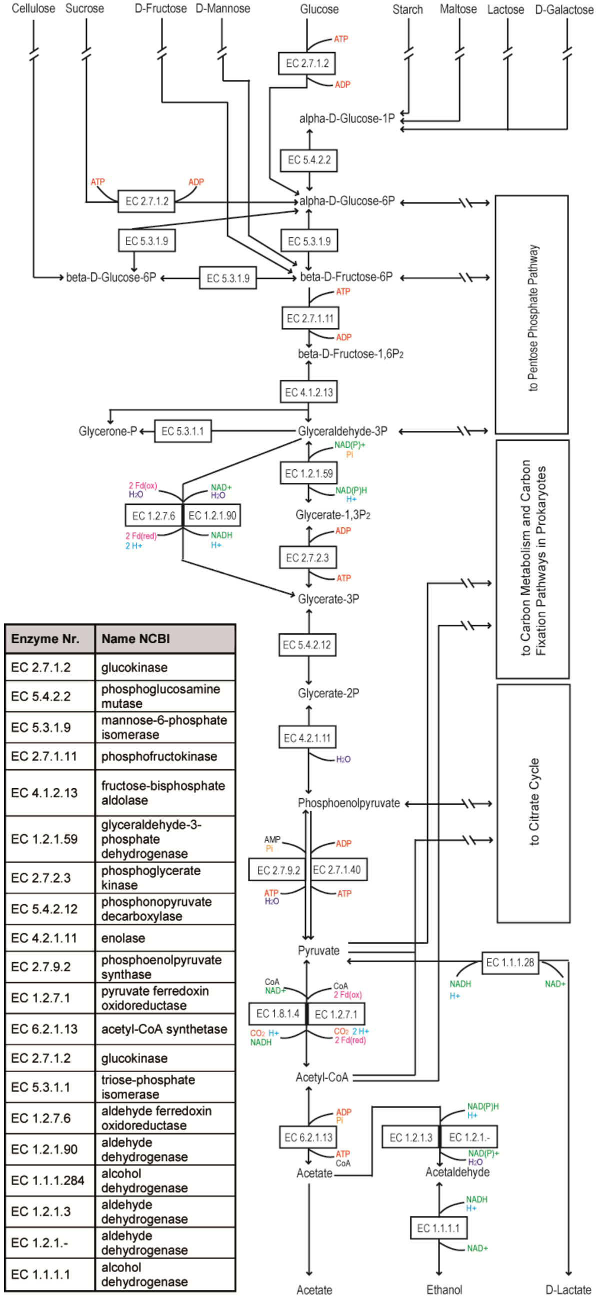
Strain	Substrate	Temp [°C]	HER [mmol L^{-1} h^{-1}]	Yield [mol mol^{-1}]	Reference
Pyrococcus furiosus	cellobiose	90	3.8	6.2	Chou et al. 2007
Pyrococcus furiosus	maltose	90	2.4	2.4	Chou et al. 2007
Thermococcus onnurineus	formate	80	2820	n.a.	Lee et al., 2012
Thermococcus onnurineus	CO	85	n.a.	1.1	Lee et al., 2012
Thermococcus kodakarensis	starch	85	3.9	1.1	Kanai et al., 2005
Thermococcus kodakarensis	pyruvate	85	3.2	3.3	Kanai et al., 2005
Desulfurococcus fermentans	starch	80	n.a.	n.a.	Perevalova et al., 2005
Halothermotrix orenii	glucose	60	n.a.	n.a.	Cayol et al., 1994
Methanococcus maripaludis	formate	37	n.a.	n.a.	Lupa et al., 2008

n.a.: not attainable
HER: hydrogen evolution rate

➢ **Formate is a cheap feedstock for H_2 production, manufactured from e.g. by-product carbon monoxide (CO) of the steel making process**

Rittmann *et al*. 2012 & 2015

Archaeal biohydrogen production



Enzyme Nr.	Name NCBI
EC 2.7.1.2	glucokinase
EC 5.4.2.2	phosphoglucosamine mutase
EC 5.3.1.9	mannose-6-phosphate isomerase
EC 2.7.1.11	phosphofructokinase
EC 4.1.2.13	fructose-bisphosphate aldolase
EC 1.2.1.59	glyceraldehyde-3-phosphate dehydrogenase
EC 2.7.2.3	phosphoglycerate kinase
EC 5.4.2.12	phosphonopyruvate decarboxylase
EC 4.2.1.11	enolase
EC 2.7.9.2	phosphoenolpyruvate synthase
EC 1.2.7.1	pyruvate ferredoxin oxidoreductase
EC 6.2.1.13	acetyl-CoA synthetase
EC 2.7.1.2	glucokinase
EC 5.3.1.1	triose-phosphate isomerase
EC 1.2.7.6	aldehyde ferredoxin oxidoreductase
EC 1.2.1.90	aldehyde dehydrogenase
EC 1.1.1.284	alcohol dehydrogenase
EC 1.2.1.3	aldehyde dehydrogenase
EC 1.2.1.-	aldehyde dehydrogenase
EC 1.1.1.1	alcohol dehydrogenase

Fig. 1 Predicted glycolysis and glyconeogenesis pathways and pyruvate metabolism of *D. amylolyticus* DSM 16532. (—//—): not all enzymes of the pathway are indicated. More detailed information on the carbon metabolism of *D. amylolyticus* DSM 16532 can be found in Supplementary Fig. 1

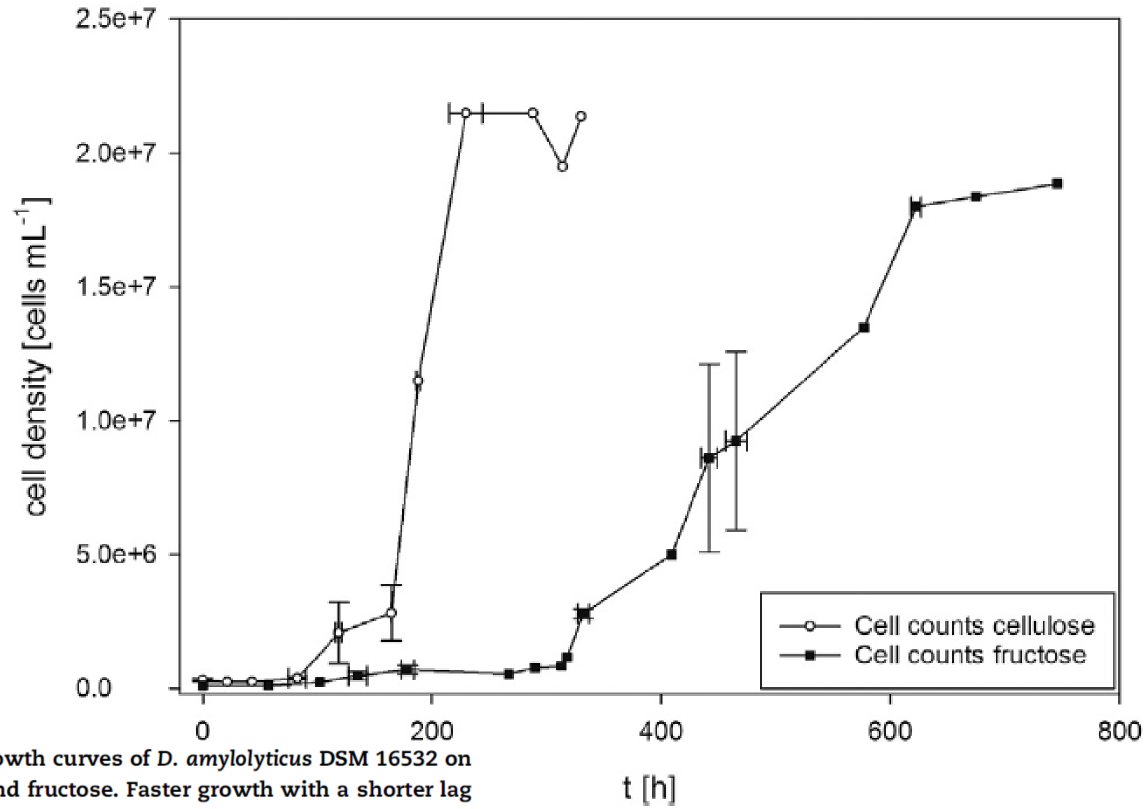


Fig. 1 – Growth curves of *D. amylolyticus* DSM 16532 on cellulose and fructose. Faster growth with a shorter lag phase could be obtained if cellulose was used as substrate.

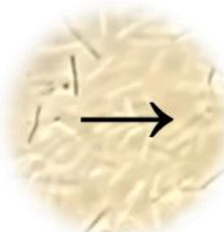
Table 3 – Comparison of $qH_{2,cell}$.

Strain	Substrate	$qH_{2,cell}$ [fmol cell^{-1} h^{-1}]	Reference
Aminobacterium colombiense DSM 12261	alanine	5.13	[27]
Clostridium butyricum CGS5	sucrose	0.09	[26]
Syntrophothermus lipocalidus	butyrate	30.46	[27]
Salmonella enterica serovar Typhimurium	glucose/formate	0.84–1.08	[25]
Desulfurococcus amylolyticus DSM 16532	cellulose	3.41	This study
Desulfurococcus amylolyticus DSM 16532	fructose	8.42	This study

Reischl *et al*. 2018, Folia Microbiol; Reischl *et al*. 2018 Int J Hydrogen Energ

5^{th} biofuel generation

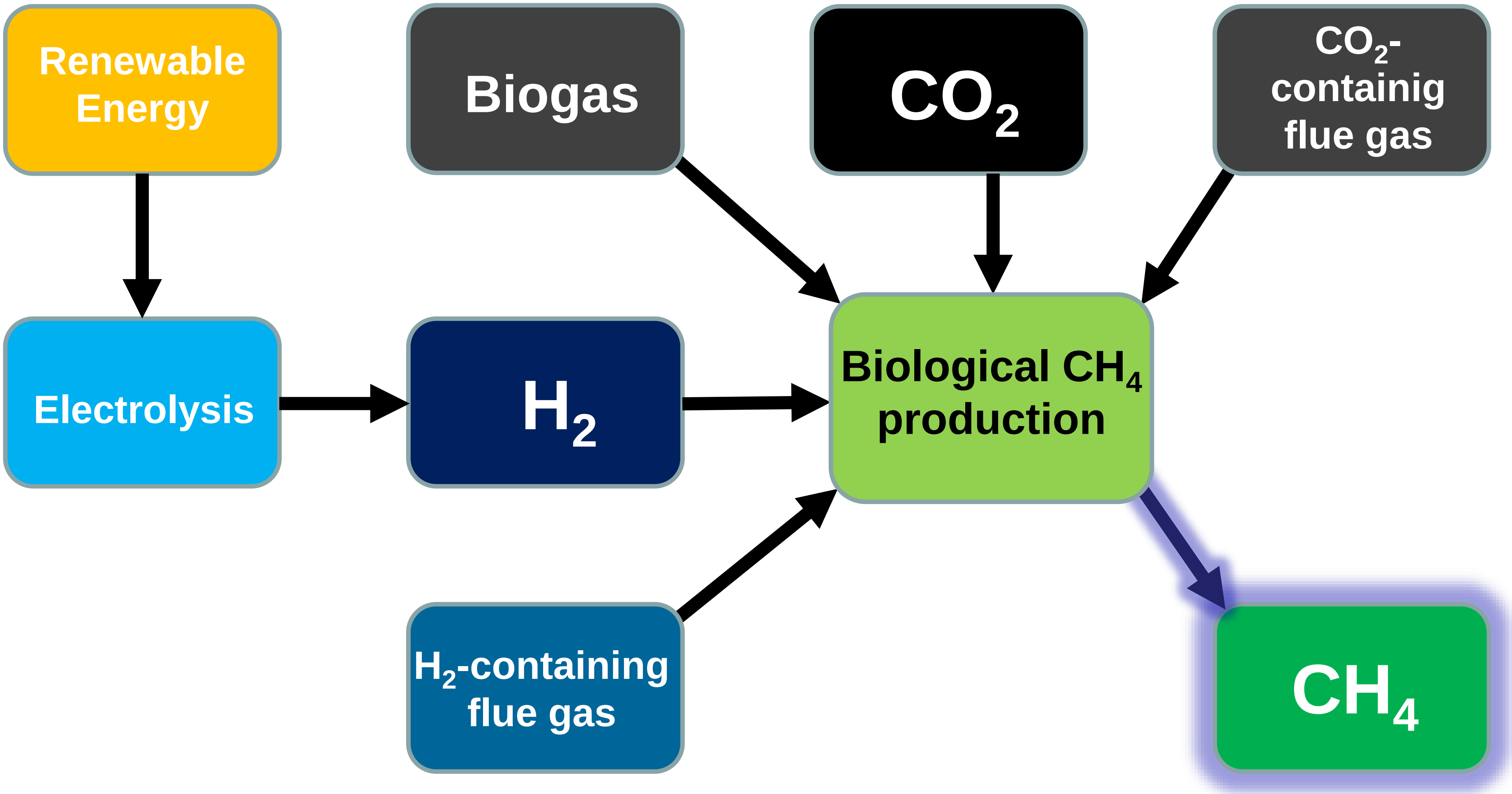
$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O$$



methanogens

Mauerhofer *et al.*, unpublished

CO_2-BMP bioprocessing



$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Seifert *et al*. 2013, Rittmann *et al*. 2014

CO_2-BMP bioprocessing

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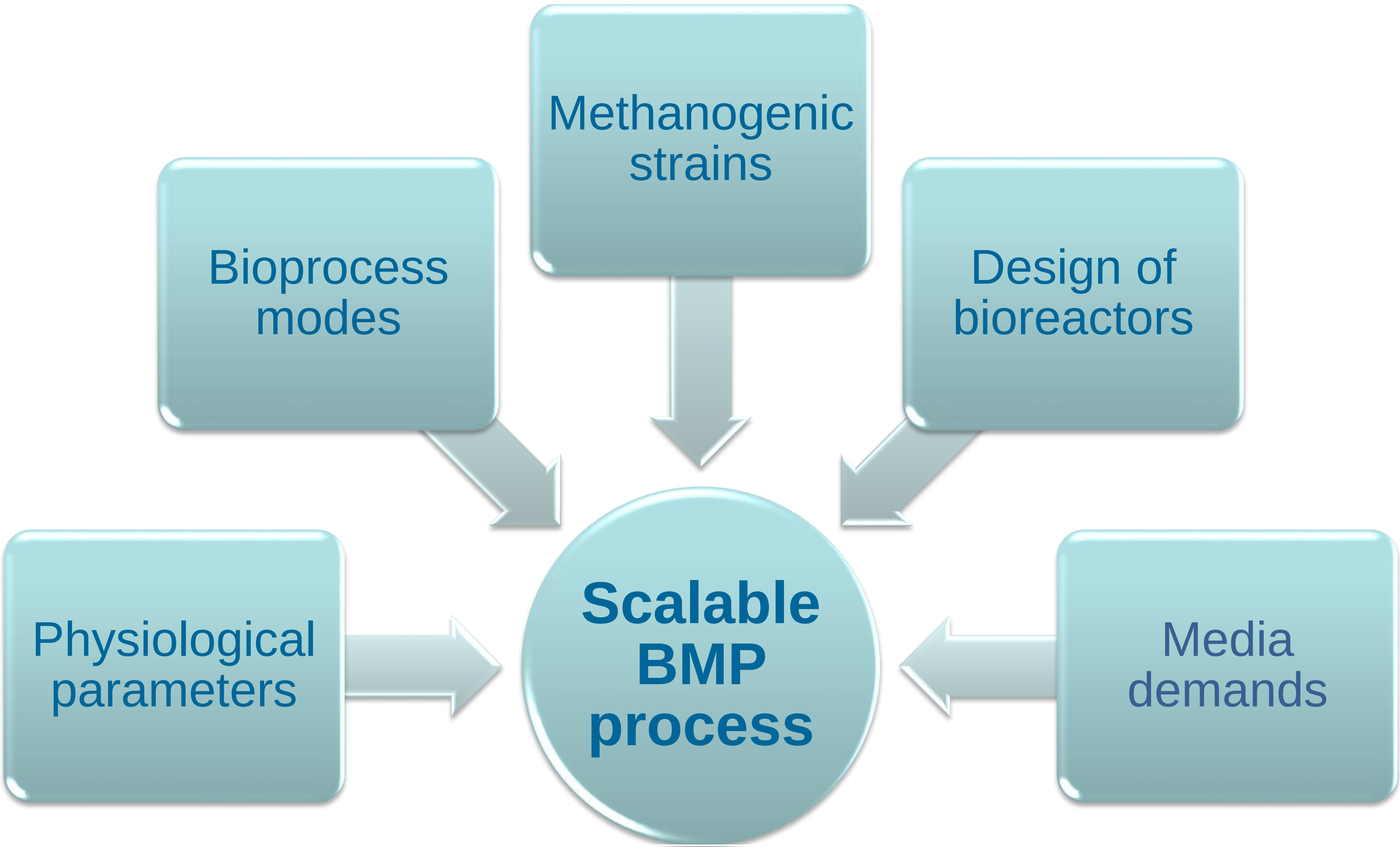
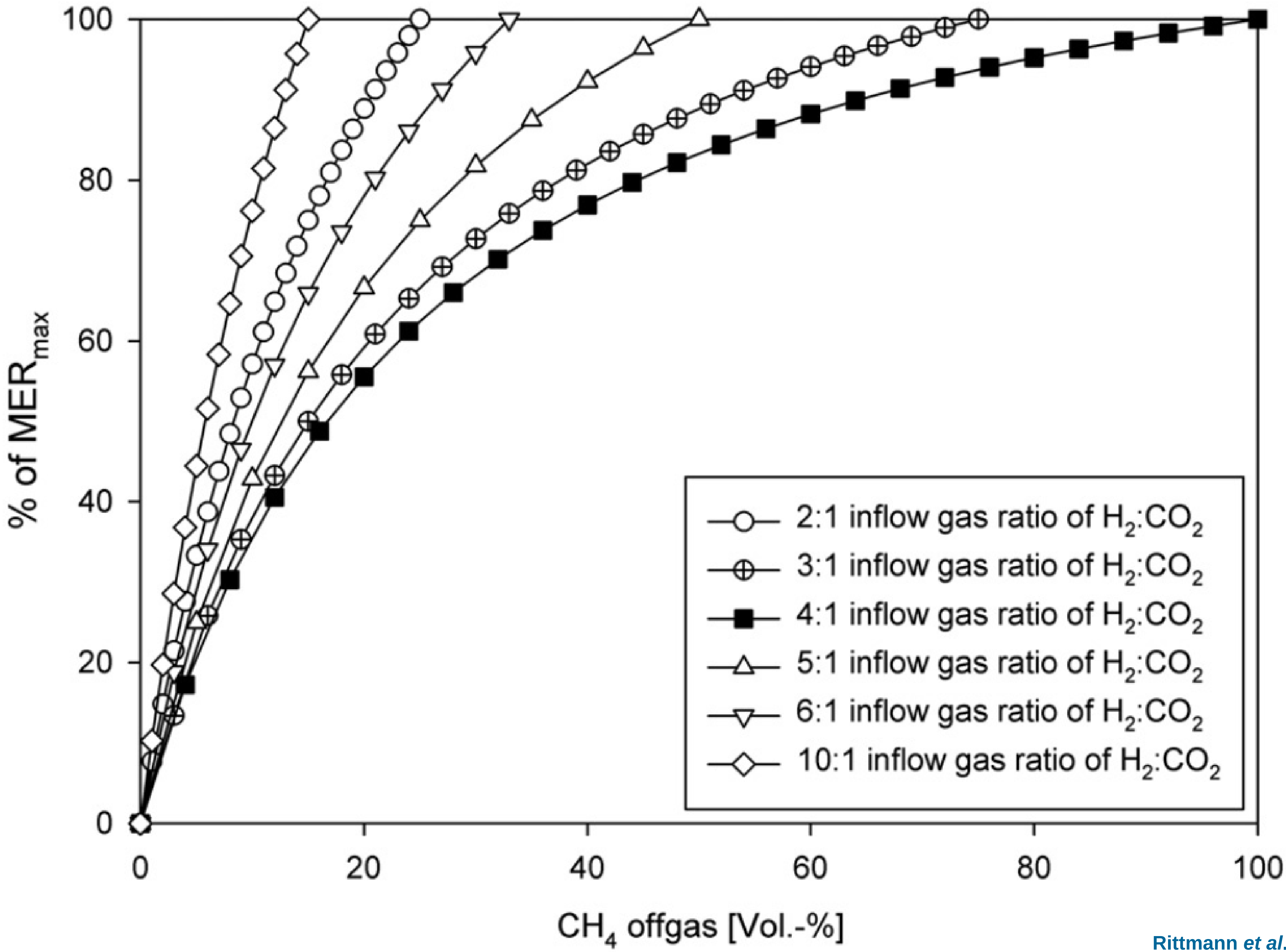


Rittmann *et al.*, 2015

CO_2-BMP bioprocessing



Rittmann *et al.*, 2015

CO_2-BMP bioprocessing

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Table 2. Overview of quantitative experiments for biological methane production in bioreactors.

Genus	Species	Strain	Cultivation modes	Bioreactor features	Gassing rate [L min^{-1}]	D [h^{-1}]	MER [mmol L^{-1} h^{-1}]	qCH_4 [mmol g^{-1} h^{-1}]	References
Methanobrevibacter	*aboriphilus*	DSM 2462	Chemostat	10 L bioreactor	0.833	0.00875		8	Morii et al., 1987
Methanobrevibacter	*aboriphilus*	DSM 2462	Chemostat	10 L bioreactor	0.833	0.01083		10	Morii et al., 1987
Methanobrevibacter	*aboriphilus*	DSM 2462	Chemostat	10 L bioreactor	0.833	0.015		11	Morii et al., 1987
Methanobrevibacter	*aboriphilus*	DSM 2462	Chemostat	10 L bioreactor	0.833	0.0179		13	Morii et al., 1987
Methanocaldococcus	*jannaschii*		Chemostat	5 L bioreactor	0.05	0.2		51	Tsao et al., 1994
Methanocaldococcus	*jannaschii*		Chemostat	5 L bioreactor	0.15	0.056		130	Tsao et al., 1994
Methanocaldococcus	*jannaschii*		Chemostat	5 L bioreactor	0.15	0.3		195	Tsao et al., 1994
Methanocaldococcus	*Jannaschii*		Chemostat	5 L bioreactor	0.23	0.056	63	175	Tsao et al., 1994
Methanocaldococcus	*jannaschii*		Chemostat	5 L bioreactor	0.23	0.3	124.8	240	Tsao et al., 1994
Methanocaldococcus	*jannaschii*		Chemostat	5 L bioreactor	0.23	0.56	130	325	Tsao et al., 1994
Methanosarcina	*barkeri*	MS	Fed-batch	2 L bioreactor	0.02		5.539		Weimer & Zeikus, 1978
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	2 L bioreactor	0.2		24.4		Morgan et al., 1997
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	2 L bioreactor	0.2		54.5		Morgan et al., 1997
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	1.3 L jar bioreactor	0.4			223	Jee et al., 1987b
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Hollow fiber bioreactor	0.023	0.26	75		Jee et al., 1988a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Hollow fiber bioreactor	0.040	0.26	94		Jee et al., 1988a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Hollow fiber bioreactor	0.016	0.26	60		Jee et al., 1988a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	3 L bioreactor	0.100	0.170		70	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	3 L bioreactor	0.155	0.170		100	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	3 L bioreactor	0.300	0.182		110	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	3 L bioreactor	0.450	0.220		115	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	3 L bioreactor	0.450	0.220		145	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Fixed-bed bioreactor (0.107 L)	0.047	0.295	236.5		Jee et al., 1988b
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Fixed-bed bioreactor (0.107 L)	0.047	0.295	152.0		Jee et al., 1988b
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Fixed-bed bioreactor (0.107 L)	0.047	0.295	156.2		Jee et al., 1988b
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Fixed-bed bioreactor (0.107 L)	0.047	0.295	147.8		Jee et al., 1988b
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Anaerobic membrane cultivation	0.01267	11.1	62.8		Jee et al., 1987a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Anaerobic membrane cultivation	0.01267	11.1	57.8		Jee et al., 1987a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Anaerobic membrane cultivation	0.01267	11.1	47.1		Jee et al., 1987a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Chemostat	Bioreactor with ceramic support (0.097 L)	0.04333	0.51	426.1		Jee et al., 1987a
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	12 L bioreactor	1.8		60	120	Pennings et al., 2000
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	12 L bioreactor	1.4		66	90	Pennings et al., 2000
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.107			167	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.214			144	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.214			127	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.214			161	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.428			174	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.428			177	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.428			178	de Poorter et al., 2007

(continued)

Rittmann *et al.*, 2015

CO_2-BMP bioprocessing

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Table 2. Continued

Genus	Species	Strain	Cultivation modes	Bioreactor features	Gassing rate [L min^{-1}]	D [h^{-1}]	MER [mmol L^{-1} h^{-1}]	qCH_4 [mmol g^{-1} h^{-1}]	References
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	3 L bioreactor	0.428			188	de Poorter et al., 2007
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	1 L glass vessel	0.130		3	111	Roennow & Gunnarsson, 1982
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	1 L glass vessel	0.130		12	46	Roennow & Gunnarsson, 1982
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	1 L glass vessel	0.126		7	48	Roennow & Gunnarsson, 1982
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	1 L glass vessel	0.126		12	37	Roennow & Gunnarsson, 1982
Methanothermobacter	*thermoautotrophicus*	DSM 1053	Fed-batch	Hollow fiber	0.016	0.26000	62		Jee et al., 1988a
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24		281	234	Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24		133	475	Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24				Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24				Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24				Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	0.5 L bioreactor	0.24				Schoenheit et al., 1980
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	Glass bioreactor (1.5 L)	1		148.7	99.1	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Fed-batch	Glass bioreactor (1.5 L)	1		223.1		Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1 L bioreactor		0.102	165	53	Rittmann et al., 2012
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1 L bioreactor		0.203	90	63	Rittmann et al., 2012
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	Glass bioreactor (1.5 L)	1	0.15	409.0	511.2	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	Glass bioreactor (1.5 L)	1	0.15	423.8	407.5	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	Glass bioreactor (1.5 L)	1	0.15	464.7	344.3	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	Glass bioreactor (1.5 L)	1	0.15	502.0	313.7	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1.5 L glass bioreactor	1.03	0.15	427.6	534.5	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1.5 L glass bioreactor	1.03	0.15	464.7	258.2	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1.5 L glass bioreactor	1.03	0.15	511.2	182.6	Peillex et al., 1990
Methanothermobacter	*marburgensis*	DSM 2133	Chemostat	1.5 L glass bioreactor	1.03	0.15	535.4	148.7	Peillex et al., 1990
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Fed-batch	16 L bioreactor	2		32	11	Gerhard et al., 1993
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Fed-batch	16 L bioreactor	2		62	19	Gerhard et al., 1993
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Fed-batch	16 L bioreactor	6		114	24	Gerhard et al., 1993
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Chemostat	2 L calorimeter	1		295		Schill et al., 1996
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Chemostat	2 L calorimeter	0.5		187		Schill et al., 1996
Methanothermobacter	*thermoautotrophicus*	DSM 3590	Chemostat	2 L calorimeter	0.2		94		Schill et al., 1996
		KN-15	Chemostat	2 L bioreactor	5	0.3–0.4	450	115	Nishimura et al., 1992
		KN-15	Chemostat	2 L bioreactor	5	0.3–0.4	930	169	Nishimura et al., 1992
		KN-15	Chemostat	2 L bioreactor	5	0.3–0.4	1280	158	Nishimura et al., 1992

Rittmann *et al.*, 2015

CO_2-BMP bioprocessing

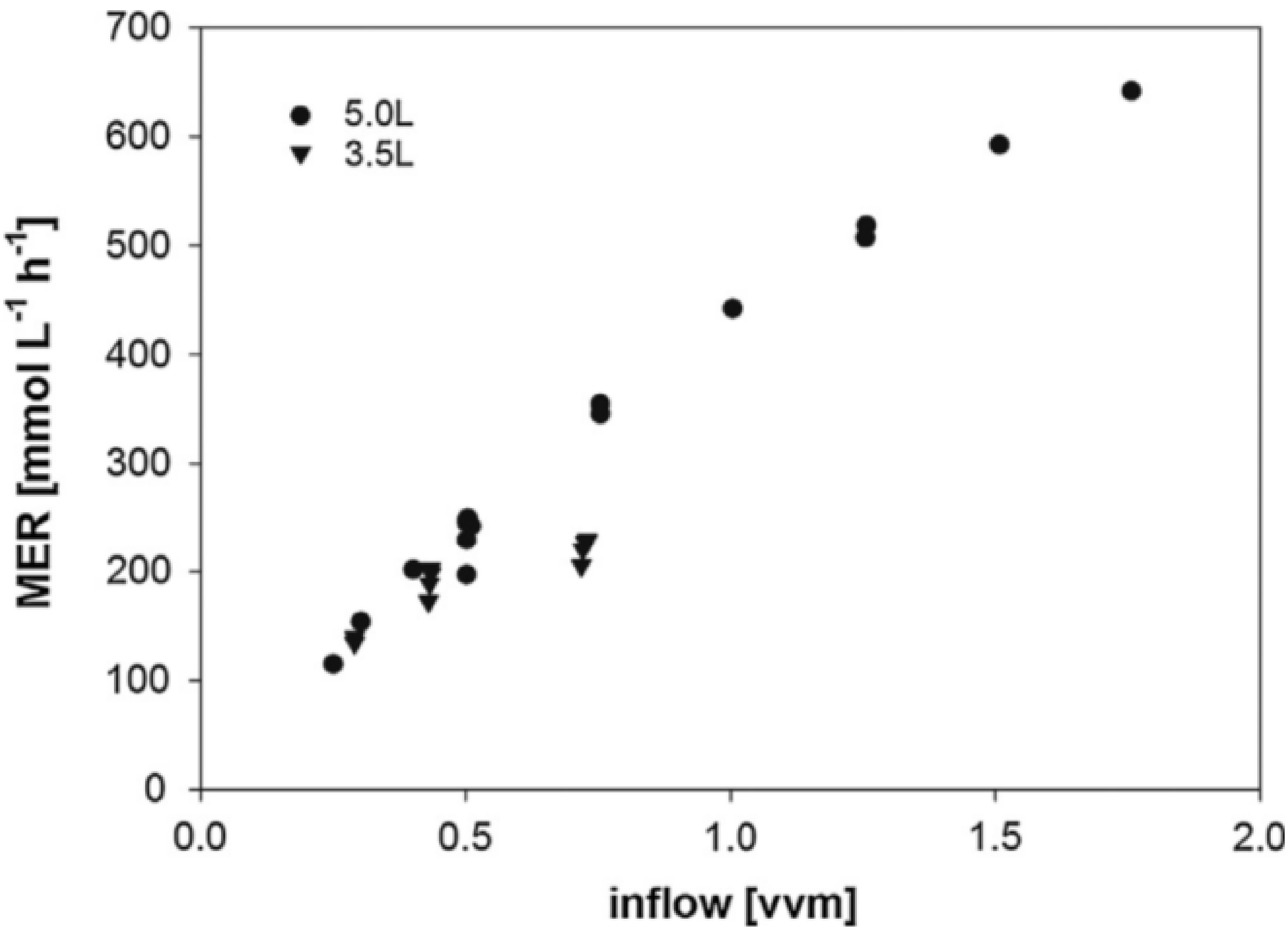


Fig. 6. Increase of MER with increased gasflow at 3.5 L and 5 L culture volume.

Seifert *et al.*, 2014

CO_2-BMP bioprocessing

(a,b) Anaerobic biofilm growing on matrix material for biomethane production in a trickle bed bioreactor. **(c)** 2L Lab-scale STR-bioreactor for biomethane production.

BMP mode	MER [mmol $L^{-1}h^{-1}$]	CH_4 [Vol.-%]	References
CSTR	1280	18.3	Nishimura et al., 1992
CSTR	530	96	Peillex et al., 1990
CSTR	950	60	Seifert et al., 2014
Fixed-bed	267	26	Jee et al., 1987
Fixed-bed	228	58	Jee et al., 1988b
Hollow fibre	145	14.5	Jee et al., 1988a
Trickle bed	1.6*	97.9	Burkhardt and Busch, 2013

* MER calculated per m^3 matrix material, MER → methane evolution rate, BMP → biological methane production

- Either high volumetric productivity (MER) or high methane concentration in the fermentation offgas can be achieved - not both in parallel!

Rittmann *et al.* 2015

CO_2-BMP bioprocessing

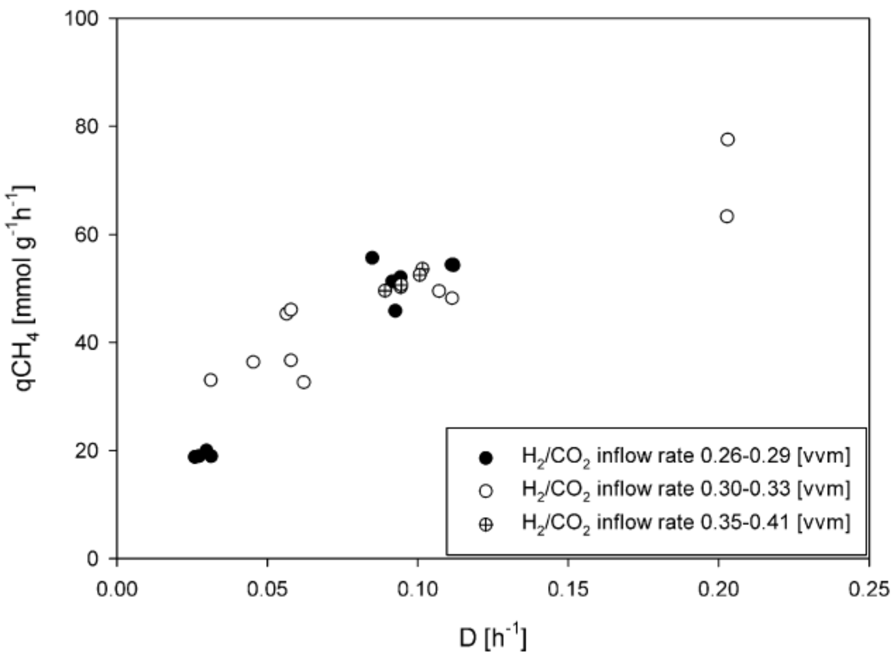


Fig. 2 – Specific methane productivity is shown as a function of the liquid dilution rate. By increasing the liquid dilution rate the specific methane productivity increased. An elevated H_2/CO_2 gassing rate ambiguously influenced qCH_4.

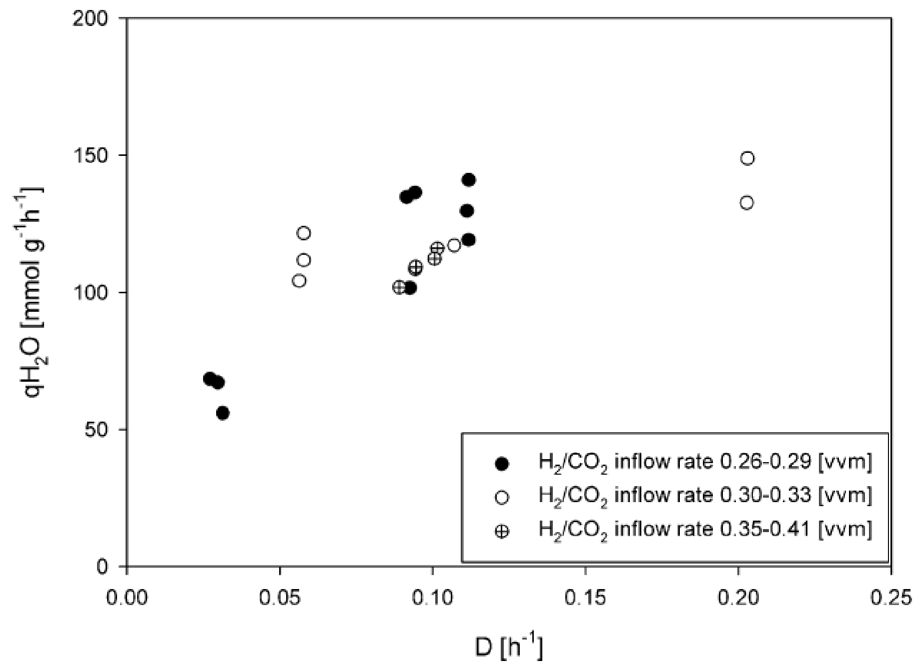
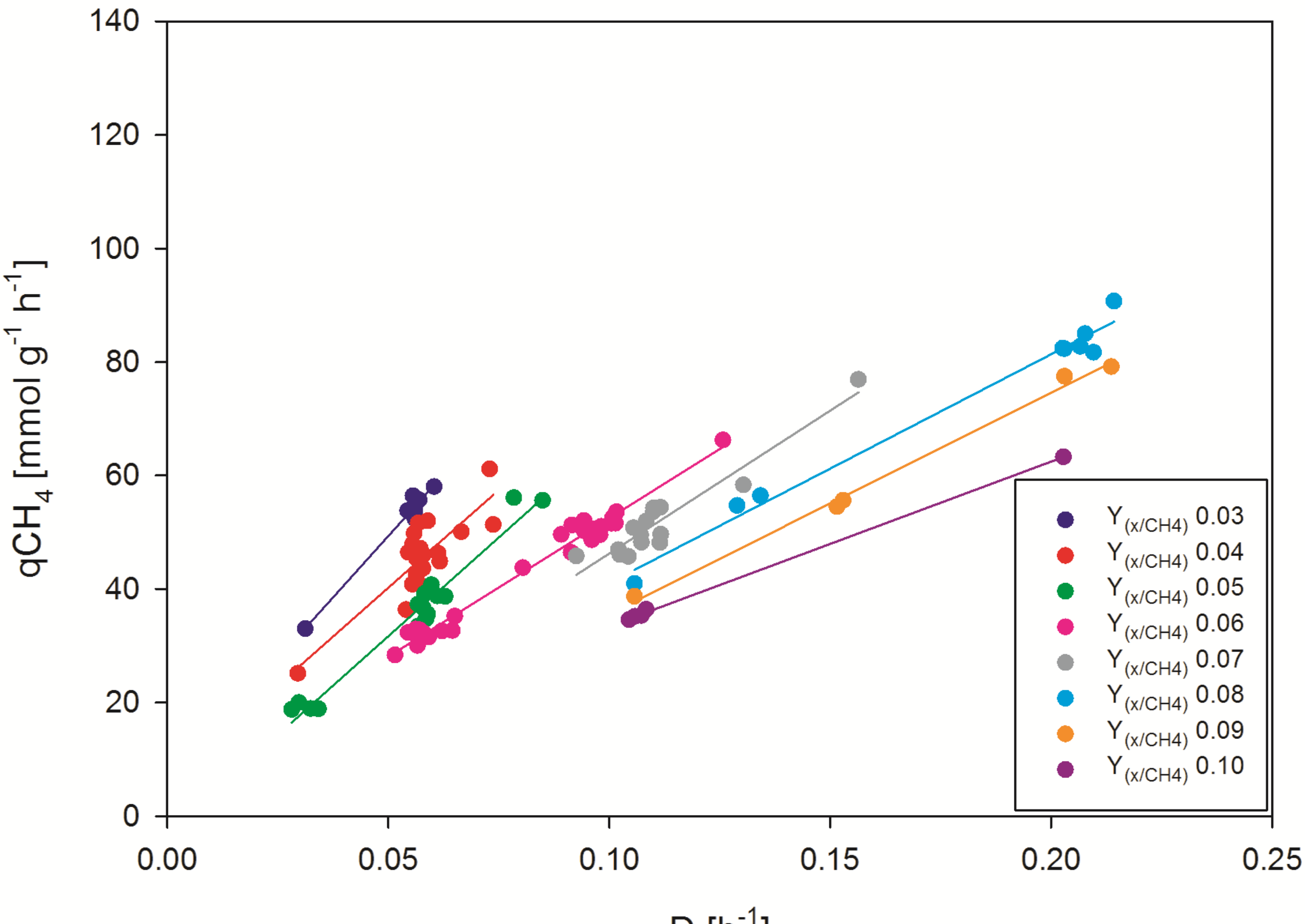


Fig. 5 – Specific water production of *M. marburgensis* is illustrated as a function of the liquid dilution rate. By increasing the liquid dilution rate the specific water production increased. An elucidation of different H_2/CO_2 gassing rates ambiguously influenced specific water productivity.

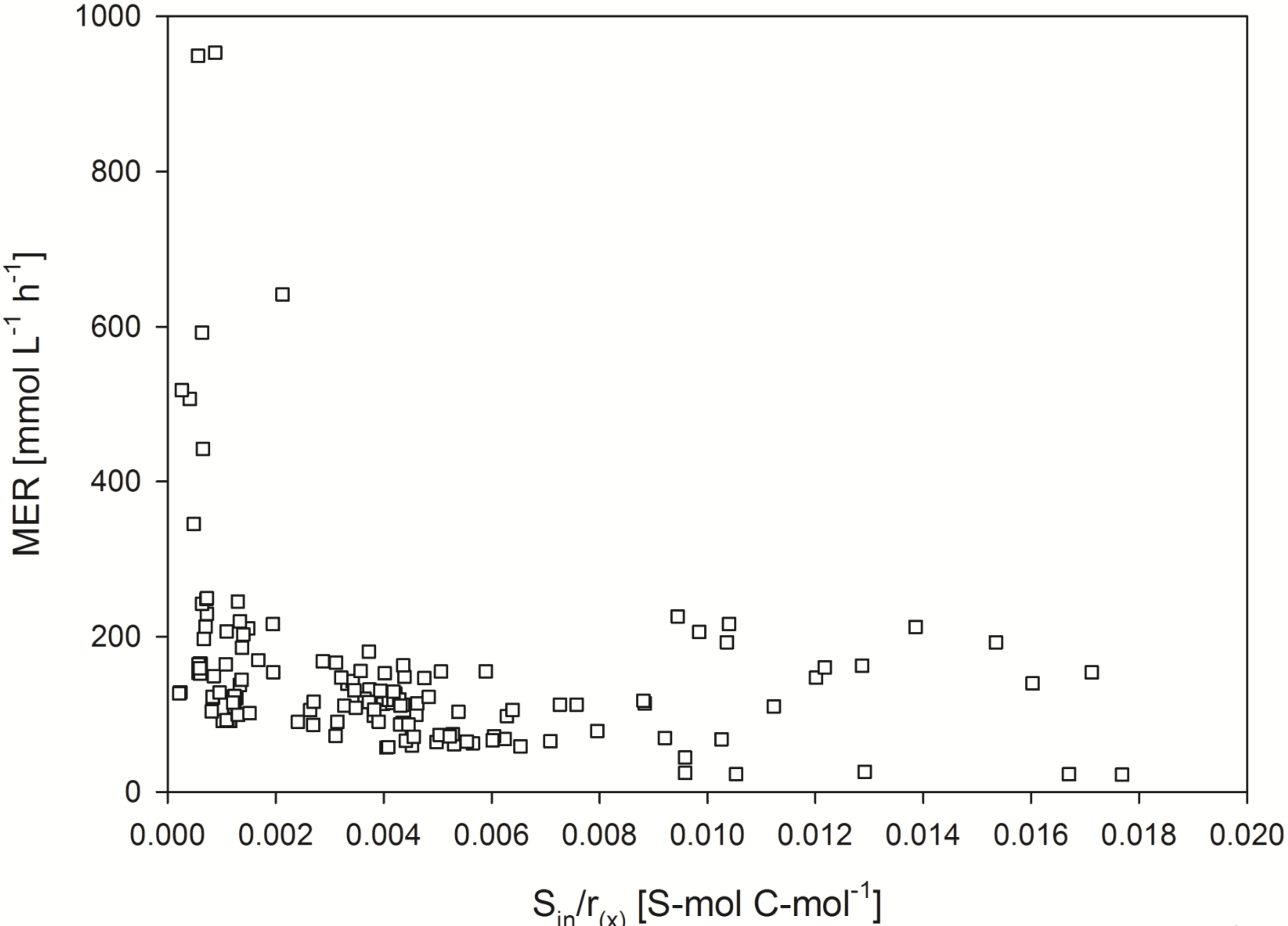
Rittmann *et al*. 2012

CO_2-BMP bioprocessing



Rittmann *et al*. 2018

CO_2-BMP bioprocessing



Rittmann *et al*. 2018

CO_2-BMP bioprocessing

- 17800 kWh a^{-1} (100m^2, 3 persons) Statistik Austria → 2.032 kWh h^{-1}

- Biological CH_4 production bioreactor produces 950 mmol L^{-1} h^{-1} = 212.294 kWh m^{-3} h^{-1}

➢ **A ~10L (C)STR would be sufficient to supply three people living a 100 m^2 flat with bioenergy!**

Biogas upgrading

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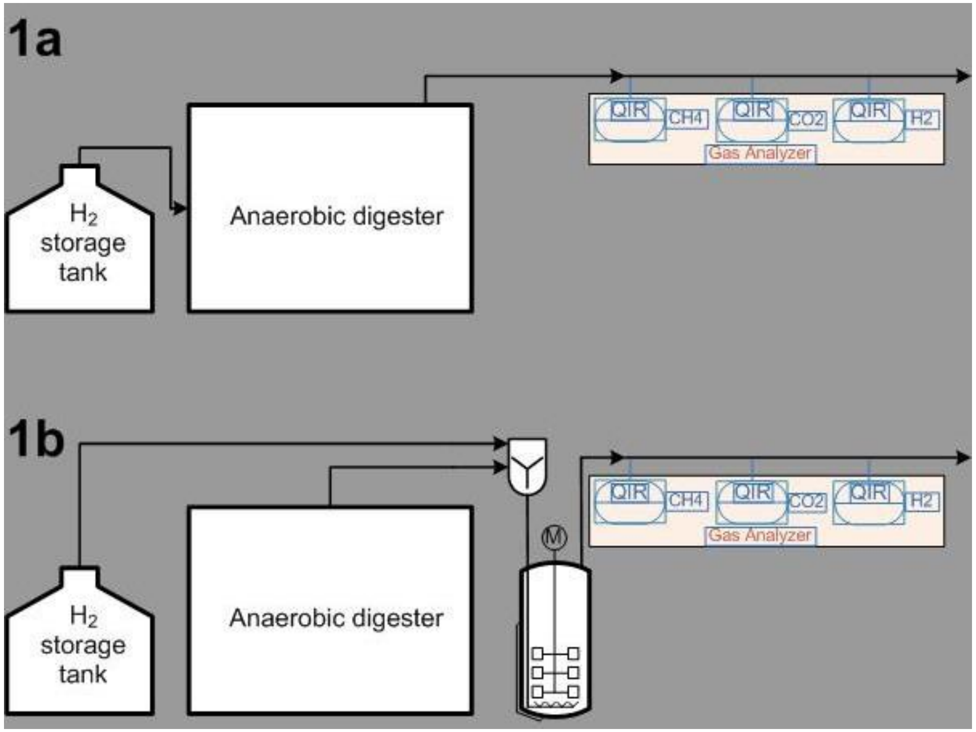

Two principle set-ups for the upgrading of biogas-to-biomethane are indicated. H_2 from renewable energy production is converted *via* water electrolysis (H_2 storage tank). The fermentation offgas needs to be analysed regarding the composition of CH_4, CO_2, H_2 (and putatively also H_2S). **1a** shows *in situ* biogas upgrading by addition of H_2 directly into the anaerobic digester. Due to the simplicity of the set-up a separate bioreactor does not to be included. In **1b** the principle set-up for *ex situ* upgrading of biogas in a separate bioreactor by contacting H_2, biogas and an enrichment culture comprising mainly of hydrogenotrophic methanogens or a pure culture of hydrogenotrophic methanogens is used for H_2/CO_2 conversion. The set-up requires an additional bioreactor but biogas (or also other CO_2 or H_2 containing industrial flue gasses) can be contacted under defined process conditions as well as by using different type of bioreactors.

- *In situ* upgrading of biogas-to-biomethane by addition of H_2 into the anaerobic digester
- *Ex situ* upgrading of biogas-to-biomethane in a separate bioreactor by contacting H_2, biogas and an enrichment culture including hydrogenotrophic methanogens
- *Ex situ* upgrading of biogas-to-biomethane in a separate bioreactor by contacting H_2, biogas and a pure culture of hydrogenotrophic methanogens

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Biogas upgrading

Upgrading technology	H_2 gassing rate [vvm]	Stirrer speed [rpm]	Temp. [°C]	Bioprocess mode, comments	Vessel and working volume	CH_4 offgas [Vol.-%]	MER [mmol L^{-1} h^{-1}]	Reference
in situ	0.0005	100	55	semi-continuous	4.5 L bioreactor, 3.5 L working volume	65 ± 3.3	0.25 *	[18]
in situ	0.0012	150	55	semi-continuous, column diffuser	1 L bottle, 0.6 L working volume	53 ± 3	0.56 *	[19]
in situ	0.0012	300	55	semi-continuous, column diffuser	1 L bottle, 0.6 L working volume	68 ± 2.5	0.66 *	[19]
in situ	0.0012	150	55	semi-continuous, ceramic diffuser	1 L bottle, 0.6 L working volume	75 ± 3.4	0.69 *	[19]
ex situ, mixed culture	0.0021	500	55	semi-continuous	1 L bottle, 0.6 L working volume	93.5 ± 4.4	1.35 *	[5]
ex situ, mixed culture	0.0042	500	55	semi-continuous	1 L bottle, 0.6 L working volume	95.4 ± 2.8	2.74 *	[5]
ex situ, mixed culture	0.0083	500	55	semi-continuous	1 L bottle, 0.6 L working volume	89.9 ± 4.1	5.25 *	[5]
ex situ, mixed culture	0.0083	800	55	semi-continuous	1 L bottle, 0.6 L working volume	94.2 ± 2.8	5.39 *	[5]
ex situ, mixed culture	0.0167	800	55	semi-continuous	1 L bottle, 0.6 L working volume	90.8 ± 2.8	10.59 *	[5]
ex situ, mixed culture	n.a.	n.a.	60	continuous culture	n.a.	n.a.	258.77 *	[20]
ex situ, mixed culture	n.a.	n.a.	60	continuous culture, with cell recycle	n.a.	n.a.	446.15 *	[20]
ex situ, mixed culture	n.a.	n.a.	37	continuous culture	n.a.	n.a.	24.75 *	[20]
ex situ, mixed culture	n.a.	n.a.	37	continuous culture, with overpressure	n.a.	n.a.	40.15 *	[20]
ex situ, pure culture	n.a.	n.a.	62	fed-batch	n.a.	96	26000 #	[21]
ex situ, pure culture	0.325	1500	65	chemostat culture, overpressure	10 L bioreactor, 5 L working volume	n.a.	n.a.	[15]
ex situ, pure culture	0.067	700	60	chemostat culture	bioreactor, 3 L working volume	n.a.	23.42 °	[22]
ex situ, pure culture	0.533	700	60	chemostat culture	bioreactor, 3 L working volume	n.a.	50.01 °	[22]
ex situ, pure culture	0.067	700	60	chemostat culture	bioreactor, 3 L working volume	n.a.	22.31 °	[22]

n.a.: not attainable
* calculated from volumetric H_2 uptake rate divided by four
# presumably the authors presented total MER (including MER from biogas production)
°calculated from volumetric methane production rate

Rittmann (2015) Advances in Biochemical Engineering/Biotechnology

(Bio)gas upgrading

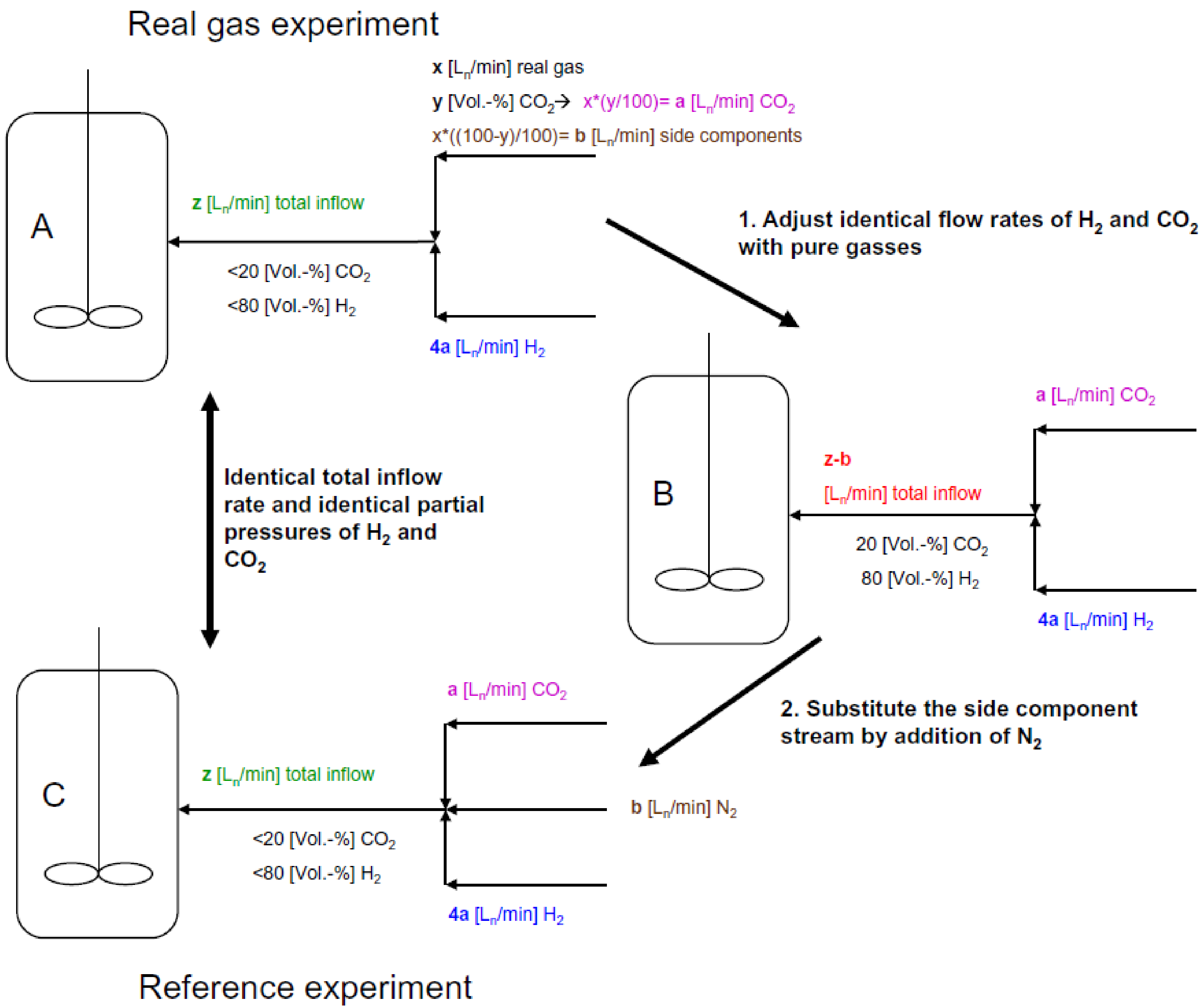

Fig. 1. Scheme of the proposed method.

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(Bio)gas upgrading

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Table 1
Composition of the tested real gasses.

Type of gas	Convertable component	Concentration (Vol.-%)	Other components
Synthetic H_2 enriched waste gas	H_2	~60	CO, CO_2, short-chain alkanes
Impure biogas	CO_2	~50	CH_4, unknown
Combustion gas	CO_2	~10	Mainly N_2, O_2

Table 2
Overview over the performed real gas and corresponding reference experiments and the resulting quotient of MER_{Real}/MER_{Ref}. Total gassing rates given as volume gas per volume liquid per minute (vvm).

	Synthetic H_2 enriched waste gas						Impure biogas		Combustion gas	
Experiment Nr.	1		2		3		4		5	
	Real gas	Reference	Real gas	Reference	Real gas	Reference	Real gas	Reference	Real gas	Reference
Reactor	2		2		1		2		1	
Total flow rate (vvm)	0.54		0.23		0.31		0.501		0.625	
Flow rate H_2 (L_n/min)	0	1.527	0	0.65835	0	0.13734	1.625	1.625	0.2224	0.2224
Flow rate CO_2 (L_n/min)	0.3	0.348	0.12	0.1409	0.029	0.03336	0	0.4048	0.0276	0.0556
Flow rate real gas/N_2 (L_n/min)	2.424	0.848	1.045	0.36575	0.218	0.0763	0.88	0.4752	0.25	0.222
Real gas content (Vol.-%)	89.0	–	89.7	–	88.3	–	35.1	–	50.0	–
Reactor volume (L)	5		5		0.8		5		0.8	
Reactor pressure (barg)	0		0		0		1.5		0	
MER_{Real}/MER_{Ref}	1.07 ± 0.08		1.12 ± 0.14		1.11 ± 0.14		0.98 ± 0.05		1.07 ± 0.12	

Seifert *et al.* 2013

Further reading – H_2

REVIEW Open Access

A comprehensive and quantitative review of dark fermentative biohydrogen production

Simon Rittmann and Christoph Herwig*

Microbial Cell Factories, 2012

Analysis of H_2 to CO_2 yield and physiological key parameters of *Enterobacter aerogenes* and *Caldicellulosiruptor saccharolyticus*

International Journal of Hydrogen Energy, 2013

*Ester Martinez-Porqueras [1], Simon Rittmann [1], Christoph Herwig**

Vienna University of Technology, Institute of Chemical Engineering, Research Area Biochemical Engineering, Gumpendorferstraße 1a, 1060 Vienna, Austria

Research review paper

One-carbon substrate-based biohydrogen production: Microbes, mechanism, and productivity

Simon K.-M.R. Rittmann [a,1], Hyun Sook Lee [b,c,1], Jae Kyu Lim [b], Tae Wan Kim [b,c], Jung-Hyun Lee [b,c], Sung Gyun Kang [b,c,*]

[a] *Archaea Biology and Ecogenomics Division, Department of Ecogenomics and Systems Biology, University of Vienna, Althanstraße 14, 1090 Wien, Austria*
[b] *Korea Institute of Ocean Science and Technology, Ansan, South Korea*
[c] *Department of Marine Biotechnology, University of Science and Technology, Daejeon, South Korea*

Biotechnology Advances, 2015

Biohydrogen production characteristics of *Desulfurococcus amylolyticus* DSM 16532

International Journal of Hydrogen Energy, 2018

*Barbara Reischl, İpek Ergal, Simon K.-M. R. Rittmann**

Metabolic reconstruction and experimental verification of glucose utilization in *Desulfurococcus amylolyticus* DSM 16532

Folia Microbiologica, 2018

Barbara Reischl [1] · İpek Ergal [1] · Simon K.-M. R. Rittmann [1]

Research review paper

The physiology and biotechnology of dark fermentative biohydrogen production

İpek Ergal [a], Werner Fuchs [b], Benedikt Hasibar [b], Barbara Thallinger [c], Günther Bochmann [b], Simon K.-M.R. Rittmann [a]

Biotechnology Advances, 2018

Further reading – CH_4

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Quantitative analysis of media dilution rate effects on *Methanothermobacter marburgensis* grown in continuous culture on H_2 and CO_2

Biomass & Bioenergy, 2012

*S. Rittmann, A. Seifert, C. Herwig**

Short Communication

Method for assessing the impact of emission gasses on physiology and productivity in biological methanogenesis

A.H. Seifert [1], S. Rittmann [1], S. Bernacchi, C. Herwig *

Vienna University of Technology, Institute of Chemical Engineering, Research Area Biochemical Engineering, Gumpendorferstraße 1a, 1060 Vienna, Austria

Bioresource Technology, 2013

Analysis of process related factors to increase volumetric productivity and quality of biomethane with *Methanothermobacter marburgensis*

A.H. Seifert, S. Rittmann, C. Herwig *

Vienna University of Technology, Institute of Chemical Engineering, Gumpendorferstraße 1a/166-4, 1060 Vienna, Austria

Applied Energy, 2014

Research article

Experimental methods for screening parameters influencing the growth to product yield ($Y_{(x/CH4)}$) of a biological methane production (BMP) process performed with *Methanothermobacter marburgensis*

Sébastien Bernacchi [1], Simon Rittmann [1,2], Arne H. Seifert [1,3], Alexander Krajete [3], Christoph Herwig [1,*]

AIMS Bioengineering, 2014

REVIEW ARTICLE

Essential prerequisites for successful bioprocess development of biological CH_4 production from CO_2 and H_2

Simon Rittmann*†, Arne Seifert*, and Christoph Herwig

Critical Reviews in Biotechnology, 2015

A Critical Assessment of Microbiological Biogas to Biomethane Upgrading Systems

Advances in Biochemical Engineering/Biotechnology, 2015

Simon K.-M.R. Rittmann

Review

Assessing the Ecophysiology of Methanogens in the Context of Recent Astrobiological and Planetological Studies

Life, 2015

Ruth-Sophie Taubner [1,2,*], Christa Schleper [3], Maria G. Firneis [1,2] and Simon K.-M. R. Rittmann [3,*]

Method for Indirect Quantification of CH_4 Production via H_2O Production Using Hydrogenotrophic Methanogens

Frontiers in Microbiology, 2016

Ruth-Sophie Taubner [1,2,3] and Simon K.-M. R. Rittmann [3]*

The physiology of trace elements in biological methane production

CrossMark

Annalisa Abdel Azim [a,b], Christian Pruckner [a], Philipp Kolar [a], Ruth-Sophie Taubner [a,c], Debora Fino [b], Guido Saracco [b,d], Filipa L. Sousa [a], Simon K.-M.R. Rittmann [a,*]

Bioresource Technology, 2017

Further reading – CH_4

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Biological methane production under putative Enceladus-like conditions

Ruth-Sophie Taubner[1,2], Patricia Pappenreiter[3], Jennifer Zwicker[4], Daniel Smrzka[4], Christian Pruckner[1], Philipp Kolar[1], Sébastien Bernacchi[5], Arne H. Seifert[5], Alexander Krajete[5], Wolfgang Bach[6], Jörn Peckmann[4,7], Christian Paulik[3], Maria G. Firneis[2], Christa Schleper[1] & Simon K.-M.R. Rittmann[1]

Nature Communications, 2018

Intact polar lipid and core lipid inventory of the hydrothermal vent methanogens *Methanocaldococcus villosus* and *Methanothermococcus okinawensis*

Lydia M.F. Baumann[a,1], Ruth-Sophie Taubner[b,1], Thorsten Bauersachs[c], Michael Steiner[b], Christa Schleper[b], Jörn Peckmann[a], Simon K.-M.R. Rittmann[b], Daniel Birgel[a,*]

Organic Geochemistry, 2018

Evidence for archaeal methanogenesis within veins at the onshore serpentinite-hosted Chimaera seeps, Turkey

J. Zwicker[a], D. Birgel[b], W. Bach[c], S. Richoz[d,e], D. Smrzka[a], B. Grasemann[a], S. Gier[a], C. Schleper[f], S.K.-M.R. Rittmann[f], E. Koşun[g], J. Peckmann[a,b,*]

Chemical Geology, 2018

Kinetics, multivariate statistical modelling, and physiology of CO_2-based biological methane production

Simon K.-M.R. Rittmann[a,*], Arne H. Seifert[b], Sébastien Bernacchi[b]

Applied Energy, 2018

Physiology and methane productivity *of Methanobacterium thermaggregans*

Lisa-Maria Mauerhofer[1] • Barbara Reischl[1,2] • Tilman Schmider[1] • Benjamin Schupp[1] • Kinga Nagy[1,3] • Patricia Pappenreiter[4] • Sara Zwirtmayr[4] • Bernhard Schuster[3] • Sébastien Bernacchi[2] • Arne H. Seifert[2] • Christian Paulik[4] • Simon K.-M. R. Rittmann[1]

Applied Microbiology and Biotechnology, 2018

RESEARCH Open Access

The physiological effect of heavy metals and volatile fatty acids on *Methanococcus maripaludis* S2

Annalisa Abdel Azim[1,2,3,4], Simon K.-M. R. Rittmann[2*], Debora Fino[3] and Günther Bochmann[1]

Biotechnology for Biofuels, 2018

Methods for quantification of growth and productivity in anaerobic microbiology and biotechnology

Lisa-Maria Mauerhofer[1] • Patricia Pappenreiter[2] • Christian Paulik[2] • Arne H. Seifert[3] • Sébastien Bernacchi[3] • Simon K.-M. R. Rittmann[1]

Folia Microbiologica, 2018