Supplementary information

Assessing the potential for up-cycling recovered resources from anaerobic digestion through microbial protein production

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Table S1. Main technical design data and general assumptions.

Feedstock mix	**Biogas yield** [a] **(Nm^{-3} biogas kg^{-1} FM)**	**N content** [b] **(g TKN-N kg^{-1} FM)**	**w.% of feedstock (on FM basis)**
Maize silage	210	2.07	10 %
Crops residues	100	0.83	10 %
Food waste	190	4.06	10 %
Pig manure	28	6.30	70 %
Weighted average of the mix	*69.4*	*5.11*	
Biogas production rate (Nm^3 h^{-1} / ton day^{-1})	500 / 14.75		
Biomass input (ton FM day^{-1})	172		
Total solids input (ton TS day^{-1}) [c]	25.4		
Nitrogen mass balance		*Recovery efficiency*	
TKN-N loading rate to AD (kg N day^{-1})	880		
NH_4^+-N release rate in AD (kg N day^{-1})	660	75 % [d]	
NH_4^+-N recovery in liquid digestate (kg N day^{-1})	528	80 % [a]	
NH_4^+-N recovery through stripping (kg N day^{-1})	475	90 % [e]	
Energy density methane (kWh Nm^{-3}), LHV	10.85		
CH_4 content raw biogas (vol.%)	60 %		
Energy density biogas (kWh Nm^{-3})	6.50		
Mass density biogas (kg Nm^{-3})	1.22		
Energy density biogas (MWh ton^{-1}_{biogas})	5.33		

**FM = fresh material*

[a] *(Weiland, 2010)*

[b] *(Drosg et al., 2015; Pintucci et al., 2017)*

[c] *TS content of substrates: manure(8.7 %), corn & crop residues (33 %) and food waste (20.8%) (Pintucci et al., 2017):*

[d] *(De Vrieze et al., 2019)*

[e] *(Menkveld & Broeders, 2018)*

Table S2. Estimation of the production cost of input materials for MP production at digester scale.

1. **Biogas production cost**	*Minimum*	***Average***	*Maximum*
Capital investment (€)[a]	1 500 00	**2 000 000**	2 500 00
CAPEX (€ ton^{-1} biogas)[b]	*18*	***25***	*31*
OPEX (€ $year^{-1}$)[c]	75 000	**150 000**	250 000
OPEX (€ ton^{-1} biogas)	*14*	***28***	*46*
Feedstock cost (€ ton^{-1} FM)[d]	2	**5.28**	10
Feedstock cost (€ ton^{-1} biogas)	*23*	***62***	*117*
Production cost (€ ton^{-1} biogas)	*56*	***115***	*194*
Production cost (€ ton^{-1} methane)[e]	*156*	***326***	*550*

[a] Assumed investment: 3000 (Min), 4000 (Avg) and 5000 (Lechtenböhmer et al.) € Nm^{-3} h^{-1} installed biogas capacity. Investment without investment subsidy or support.
[b] Depreciation period of 20 years, 3 % interest rate.

[c] Assuming 5 % (Min), 7.5% (Avg) and 10 % (Lechtenböhmer et al.) of the total investment per year.

[d] Maize silage was assumed to have a feedstock cost of 32.8 € ton^{-1} FM and food waste a cost of 20 € ton^{-1} FM (including transportation). Agricultural residues and manure were assumed to come in for free.
[e] Assumed methane content is 60 vol.%.

2. **Ammonia recovery cost**	*Minimum*	***Average***	*Maximum*
CAPEX (€ ton^{-1} N recovered)	*230*	***345***	*460*
OPEX (€ ton^{-1} N recovered)[a]	*770*	***1 155***	*1 540*
Total N recovery cost (€ ton^{-1} N recovered)	*1 000*	***1 500***	*2 000*

[a] Based on an influent stream containing a NH_3-N concentration of > 4 g L^{-1}.

3. **Hydrogen production cost**	*Minimum*	***Average***	*Maximum*
Total production cost (€ ton^{-1} H_2)	*1 800 [b]*	***2 600 [a]***	*4 400 [c]*

[a] Future predicted levelized cost for hydrogen production using PEM electrolysis at an electricity price of 44 € per MWh. (Ayers et al., 2010)
[b] (Gökçek, 2010)

[c] Current cost for hydrogen production using PEM electrolysis at an electricity price of 44 € per MWh. (Ayers et al., 2010)

4. **Oxygen production cost[a]**	*Minimum*	***Average***	*Maximum*
	26	***30***	*34*

[a] Only for MOB case, as for the HOB case oxygen is produced via electrolysis, and costs are allocated to hydrogen.

5. **Microbial protein production**	*Minimum*	***Average***	*Maximum*
Capital investment (€ m^{-3} $_{reactor}$)	*3 000*	***5 000***	*8 000*
OPEX (€ ton^{-1} MP)	*100*	***200***	*300*

6. ***Dewatering and drying***	*Minimum*	***Average***	*Maximum*
Centrifugation (€ ton MP^{-1})	-	***70***	-
Spray drying (€ ton MP^{-1})	-	***90***	-

[b] (Pikaar et al., 2018b)

Table S3. Comparison between methane-oxidizing bacteria and hydrogen-oxidizing bacteria used in MP production.

	Methane-oxidizing bacteria	*Hydrogen-oxidizing bacteria*
Cell yield (g CDW g^{-1} COD)	0.19 [a]	0.28 [b]
Protein content (% Protein on CDW)	60 % [c]	75 % [d]
Volumetric production rate (kg CDW m^{-3} h^{-1})	4 [e]	2.28 [f]
N content (% N on CDW)	12 %	12%

[a] (Higgins et al., 1981)
[b] (Ishizaki & Tanaka, 1990)
[c] (Yazdian et al., 2005)
[d] (Volova & Barashkov, 2010)
[e] (Ritala et al., 2017)
[f] (Tanaka et al., 1995)

Table S4. Input feed to produce 1 ton MP via HOB *vs.* MOB.

	Feed (ton)					**Product (ton)**
Case	CH_4	CO_2	NH_3	H_2	O_2	Microbial protein
MOB	2.20	-	0.20	-	2.50	1
HOB	-	3.31	0.16	0.79	2.05	1

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