Supplementary Information

Upcycling of biowaste carbon and nutrients in line with consumer confidence: the "full gas" route to single cell protein

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1. Supplementary information

In the present section, additional details regarding the assumptions, the calculation and the results of this study are presented under the form of supporting tables.

Table S1. Composition and properties of the specific biowaste substrates considered to define the final reference average values

Biowaste	Reference in Phyllis database[1]	Water content (wt%)	VS content (% dry wt)	LHV (MJ/kg)	C content (% dry wt)	N content (% dry wt)	P content (% dry wt)
Lignocellulosic biomass	Barley straw #3169	12%	76%	17.43	46.2%	0.60%	0.04%
	Corn stalk #2790	8%	73%	15.76	44.8%	0.85%	-
	Poplar #700	5%	85%	18.19	49.4%	0.23%	0.01%
	Avg.	**8%**	**78%**	**17.13**	**46.8%**	**0.56%**	**0.02%**
Sewage sludge	Sewage sludge #658, #1178, #3004		54%	14.03	34.0%	4.70%	
			52%	14.19	33.7%	5.38%	0.37%
			52%	12.46	30.9%	4.76%	
	Avg.	**>98%**	**52%**	**13.56**	**32.9%**	**4.95%**	**0.37%**
Organic Fraction of Municipal Solid Waste	Organic wet fraction municipal waste #3198	57%	52%	14.52	34.0%	1.73%	0.63%
	Organic domestic waste, the Netherlands #1341	54%		15.00	42.1%	1.75%	-
	Municipal solid waste, organic wet fraction #1300	54%		16.86	42.1%	1.78%	
	Organic domestic waste #3199		53%	14.43	34.4%	1.69%	0.06%
	Avg.	**55%**	**53%**	**15.20**	**38.3%**	**1.74%**	**0.35%**
Manure	Cattle manure, fresh #1882		70%	16.19	45.4%	0.96%	0.21%
	Cow manure #2833	83%	76%		28.6%	1.50%	0.30%
	Pig manure #1366	92%	51%	12.83	35.0%	2.79%	-
	Avg.	**87%**	**66%**	**14.51**	**36.3%**	**1.75%**	**0.25%**

Table S2. Biogas production through AD treatment of biowastes.

Biowaste	Mass (ton dry dw)	VS content (% dry wt)	Biogas produced (Nm^3)			VS destruction (%)[b]	AD digestate residual mass (ton dry wt)
			Biogas[a]	CH_4	CO_2		
Sewage	1.0	52.5%	251.9	151.2	100.8	58.3%	0.69
Manure	1.0	65.9%	267.2	160.3	106.9	49.2%	0.68

[a] See Table S4 for the average biochemical methane potential considered for each substrate. Biogas is assumed to be 60% CH_4 and 40% CO_2.
[b] Volatile solids destruction is calculated based on the amount of biogas produced, see paragraph 2.1.3 in the manuscript.

Table S3. Syngas production through Py/Gs treatment of biowastes

Biowaste	Mass (ton dry dw)	Syngas produced through Py/Gs (Nm^3)					
		Syngas[a]	Syngas processing	CO	H_2	CH_4	CO_2
OFMSW	1.0	506.8	no	116.6	192.6	45.6	116.6
			yes	0.0	525.7	298.1	0.0
Lignocellulosics	1.0	570.9	no	131.3	216.9	51.4	131.3
			yes	0.0	592.3	335.8	0.0

[a] See Table 4 in the manuscript for the syngas yield considered for each substrate

Table S4. Range of values used to perform the parametric analysis. The carbon content of biochar was assumed to be constant under all scenarios.

Parameter	Low value	Average value	High value
Biochemical methane potential of sewage sludge (Nm^3 CH_4/ton VS) [27]	230	288	346
Biochemical methane potential of manure (Nm^3 CH_4/ton VS) [28]	195	243	292
Cold gas efficiency (%)[2]	20	40	60
Biochar yield (% wt)[3]	14.8	18.5	22.0
Biochar carbon content (% wt)[3]	81.5		
N conversion efficiency as NH_3 (% wt)[4]	60	75	90

Table S5. Assumptions and calculations used to define the energy requirements of mechanical dewatering and the final water content of the co-substrate for combined treatment settings.

Process stage	Parameter	Value	Unit	Remarks and references
Co-substrate generation	AD digestate water content	96%	wt%	AD digestate resulting from the AD of both sewage sludge and manure is considered to have a 4% of dry solids content[1]
	Dewatered AD digestate water content	70%	wt%	AD digestate is mechanically dewatered through centrifuging[1]
	Mass of AD digestate	0.69	ton dry wt	Mass of AD digestate resulting from the AD of 1 ton dry wt of biowaste (average of sewage sludge and manure). See Table S2
	Wet weight of AD digestate	2.31	ton	Wet weight based on a 70% water content
	Wet weight of OFMSW	2.22	ton	Wet weight based on a 55% water content (see Table S1)
	Wet weight of lignocellulosic biomass	1.09	ton	Wet weight based on a 8% water content (see Table S1)
	Co-substrate water content	52%	wt%	Calculated as the weighted average of AD digestate, Lignocellulosics and OFMSW
AD digestate dewatering	Specific energy demand for AD digestate centrifuging	0.70	kWh/ton	A decanter centrifuge used in industrial settings is considered[5]
	Energy demand for AD digestate dewatering	11.99	kWh	Energy needed to dewater AD digestate at 96% water content in order to obtain a final mass of solid dry wt of 0.69 ton
	Combined heat and power (CHP) generation efficiency	35	%	Electrical efficiency assumed for a CHP unit fed with biogas. Note that electrical efficiencies as high as 40% have been reported[6]
	Energy demand for AD digestate dewatering through CHP	123.30	MJ	Primary energy needed to provide electrical energy to the decanter centrifuge through the CHP unit. 1 kWh is equal to 3.6 MJ
	Low heating value of biomethane	35.80	MJ/Nm^3	[7]
	Average biomethane produced from biowaste	155.75	Nm^3/ton dry wt	Value obtained by averaging the biomethane potential of sewage sludge and manure, see Table S2

	Total primary energy available from biomethane	5575.85	MJ	Energy in the biomethane produced by digesting 1 ton dry wt of biowaste

Parameter	Value	Unit	Remarks and references
Amount of biowaste needed to produce SCP	9.8	Dry ton biowaste /ton SCP	Mass of biowaste to be treated in order to produce 1 ton SCP. This value is based on a SCP potential of 102.16 kg SCP/ton biowaste (see Table S10)
Amount of carbon captured into biochar (CCS)	4.1	ton CO_2-eq/ton SCP	This value is calculated by considering an average carbon capture and storage potential of 29.9% (see Table S10) and an average biowaste carbon content of 38.6% (see Table S1)

	Share of biomethane primary energy required for AD digestate dewatering	2.21%	% of total primary energy	Share of primary energy from the produced biomethane that would be required to provide electricity to the centrifuging step through a CHP unit

Table S6. Assumptions and calculations performed to identify the amount of nutrients embedded in the AD digestate deriving from sewage sludge and manure and obtained after mechanical dewatering. The residual fraction of nutrients here calculated was applied to the N and P available from sewage sludge and manure reported in Table S1, and further used to identify the amount of nutrients available for recovery through thermochemical Py/Gs treatment under combined treatment settings.

Parameter	Value		Unit	Remarks and references
	Sewage sludge	Manure		
AD digestate water content	96%		wt%	AD digestate resulting from the AD of both sewage sludge and manure is considered to have a 4% of dry solids content[1]
Dewatered AD digestate water content	70%		wt%	AD digestate is mechanically dewatered through centrifuging[1]
Mass of AD digestate	0.69	0.68	ton dry wt	Mass of AD digestate resulting from the AD of 1 ton dry wt of biowaste. See Table S2
Wet weight of AD digestate	17.25	17.00	ton	Wet weight based on a 96% water content
Amount of water removed	16.56	16.32	m^3	Water removed during mechanical AD digestate dewatering
Fraction of residual water	9.7%	9.7%	wt%	Fraction of initial water that is retained in the dewatered AD digestate
Amount of particulate nutrients (N and P)	41.7%	51.0%	wt%	Percentage of nutrients that are embedded in the solid AD digestate matrix, which is obtained by assuming that the share of VS that is not degraded during AD retains the nutrients in a particulate form (see Table S2)
Amount of dissolved nutrients (N and P) in the dewatered AD digestate	5.8%	4.9%	wt%	Obtained by multiplying the amount of residual water by the percentage of VS destruction during AD, which corresponds to the amount of nutrients released into a water-soluble form
Fraction of nutrients (N and P) from the biowaste residual in the AD digestate	47.5%	55.9%	wt%	Overall balance of the nutrient fraction that is still available into the AD digestate and that can be recovered through Py/Gs treatment

CO_2 emissions for SCP production	1.7	ton CO_2-eq/ton SCP	Emissions are calculated based on a LCA study on SCP production using biomethane from AD.[8] It is here assumed that the carbon capture and utilization (CCU) potential has been already considered in the overall balance indicated by the LCA study
Final CO_2 balance	-2.4	ton CO_2-eq/ton SCP	Obtained by subtracting the amount of CO_2-eq captured in biochar from the CO_2 emissions estimated in the LCA study on SCP production

Parameter		Value	Unit	Remarks and references
Social cost of carbon		42.0	$/metric ton CO_2	Cost factor calculated for 2020 at a discount rate of 3%[10]
CO_2 emission factors	SCP	-2.4	ton CO_2-eq/ton feed additive	See Table S7
	Soybean meal	14.0		The CO_2 emission factor derives from an LCA study that considers land use change emissions due to use of rainforest land (non-tillage production scenario)[11]
	Fishmeal	2.6		Emission factor based on LCA study on fishmeal production[8]
Social cost of feed additive production	SCP	-102.6	$/ton feed additive	Calculated by multiplying the CO_2 emission factors by the social cost of carbon
	Soybean meal	588.0		
	Fishmeal	109.2		

Table S7. Estimation of the overall CO_2 balance for SCP production under sub-scenario 1.4.

Table S8. Estimation of SCP production costs based on the study of Pikaar et al. (2018).[9] The table reports the production pathways (*SCP pathway*), direct expenses for production (*Production cost*) and the total costs (*Total costs*) for producing SCP using gaseous substrates based on dedicated crops (biogas for MOB obtained through AD of energy maize and syngas for HOB obtained through gasification of a *Miscanthus* species). The cost section reports expenses for conventional gas-based SCP production requiring virgin mineral nutrients (*N & P*), aeration (*O_2*), running costs for fermentation (*Mixing & pumping*) and final processing (*SCP dewatering and drying*).

SCP pathway	Production costs ($)							Total costs	
	Annuity of capital cost	Gas substrate cost	O_2	N & P	Mixing & pumping	SCP dewatering and drying	Overhead	$/ton SCP	$/ton SCP (protein-equivalent)
CH_4-oxidizing bacteria	203	831	109	149	38	160	203	1692	2417
H_2-oxidizing bacteria		666	90					1507	2153

Adjusted cost of feed additive	SCP	1497	$/ton feed additive	Calculated by subtracting the social cost of carbon from the SCP average production cost of MOB and HOB (see Table S8)
	Soybean meal	959		Calculated by summing the social cost of carbon to the 5-years average (2015-2020) market price of soybean meal (371 $/ton) and of fishmeal (1466 $/ton).[12]
	Fishmeal	1575		
Adjusted cost of feed additive (protein-equivalent)	SCP	1996-2303	$/ton feed additive (protein-equivalent)	Calculated by considering a SCP protein content ranging between 65 and 75%
	Soybean meal	2398-3197		Calculated by considering a soybean meal protein content ranging between 30 and 40%
	Fishmeal	2423-2864		Calculated by considering a fishmeal protein content ranging between 55 and 65%

Table S9. Calculations used to estimate the adjusted cost of soybean meal, fishmeal and SCP feed additives

Table S10. Specific values obtained from the calculations, divided by sub-scenario and by type of biowaste considered

Sub-scenarios		1.1		1.2		1.3		1.4		2.3		2.4		2.3		2.4	
Treatment		AD	Py/Gs	AD	Py/Gs	AD	Py/Gs	AD	Py/Gs	AD	Py/Gs	AD	Py/Gs	AD	Py/Gs	AD	Py/Gs
Specific SCP production potential (kg SCP/ton biomwaste	Sewage	61.00	0.00	61.00	0.00	61.00	18.92	61.00	51.66	61.00	0.00	61.00	0.00	61.00	33.19	61.00	56.45
	Manure	64.70	0.00	64.70	0.00	64.70	30.57	64.70	53.80	64.70	0.00	64.70	0.00	64.70	34.57	64.70	58.79
	OFMSW	0.00	30.57	0.00	83.45	0.00	30.57	0.00	83.45	0.00	53.61	0.00	91.18	0.00	53.61	0.00	91.18
	Lignocellulosics	0.00	29.17	0.00	94.01	0.00	29.17	0.00	94.01	0.00	54.65	0.00	102.72	0.00	54.65	0.00	102.72
Average SCP production potential (kg SCP/ton biowaste)		31.42	14.93	31.42	44.36	31.42	27.31	31.42	70.73	31.42	27.07	31.42	48.47	31.42	44.00	31.42	77.28
Total SCP production potential (kg SCP/ton biowaste)		**46.36**		**75.79**		**58.73**		**102.16**		**58.49**		**79.90**		**75.43**		**108.71**	
Specific SCP CCU potential (% Carbon from biowaste captured in SCP)	Sewage	6.17%		6.17%		6.17%	1.82%	6.17%	4.98%	6.17%		6.17%		6.17%	3.36%	6.17%	5.71%
	Manure	9.46%		9.46%		9.46%	4.04%	9.46%	7.49%	9.46%		9.46%		9.46%	5.05%	9.46%	8.60%
	OFMSW		4.04%		11.02%	0.00%	2.75%	0.00%	11.02%		7.43%		12.64%	0.00%	7.43%	0.00%	12.64%
	Lignocellulosics		1.98%		10.16%	0.00%	1.98%	0.00%	10.16%		6.20%		11.65%	0.00%	6.20%	0.00%	11.65%
Average SCP CCU potential (% Carbon from biowaste captured in SCP)		7.82%	3.01%	7.82%	10.59%	3.91%	2.65%	3.91%	8.41%	7.82%	6.82%	7.82%	12.15%	3.91%	5.51%	3.91%	9.65%
Total SCP CCU potential (% Carbon from biowaste captured in SCP)		**5.41%**		**9.20%**		**6.55%**		**12.32%**		**7.32%**		**9.98%**		**9.42%**		**13.56%**	
Biochar CCS potential (% Carbon from biowaste captured in SCP)	Sewage		0.00%		0.00%		19.94%		19.94%		0.00%		0.00%		19.94%		19.94%
	Manure		39.35%		39.35%		39.35%		39.35%		39.35%		39.35%		39.35%		39.35%
	OFMSW		0.00%		0.00%		28.05%		28.05%		0.00%		0.00%		28.05%		28.05%
	Lignocellulosics		32.22%		32.22%		32.22%		32.22%		32.22%		32.22%		32.22%		32.22%
SCP Global potential (Mt)	Low scenario - Sewage + Manure	33.52		33.52		46.72		61.64		33.52		33.52		51.59		64.25	
	Low scenario - OFMSW	4.08		11.13		4.08		11.13		7.15		12.16		7.15		12.16	
	Low scenario - Lignocellulosics	21.07		67.90		21.07		67.90		39.47		74.19		39.47		74.19	
	LOW SCENARIO	**58.67**		**112.54**		**71.86**		**140.67**		**80.14**		**119.86**		**98.21**		**150.59**	
	High scenario -Sewage + Manure	149.89		149.89		208.90		275.64		149.89		149.89		230.68		287.29	
	High scenario - OFMSW	18.22		49.75		18.22		49.75		31.96		54.36		31.96		54.36	
	High scenario - Lignocellulosics	75.11		242.03		75.11		242.03		140.70		264.45		140.70		264.45	
	HIGH SCENARIO	**243.22**		**441.67**		**302.23**		**567.43**		**322.54**		**468.70**		**403.34**		**606.11**	
SCP Global CCU potential (Gt CO_2-eq)	Low scenario - Sewage + Manure	0.05		0.05		0.07		0.10		0.05		0.05		0.08		0.10	
	Low scenario - OFMSW	0.01		0.02		0.00		0.02		0.01		0.02		0.01		0.02	
	Low scenario - Lignocellulosics	0.02		0.13		0.02		0.13		0.08		0.14		0.08		0.14	
	LOW SCENARIO	**0.08**		**0.20**		**0.10**		**0.24**		**0.14**		**0.22**		**0.17**		**0.27**	
	High scenario -Sewage + Manure	0.24		0.24		0.33		0.43		0.24		0.24		0.36		0.45	
	High scenario - OFMSW	0.03		0.08		0.02		0.08		0.06		0.10		0.06		0.10	
	High scenario - Lignocellulosics	0.09		0.45		0.09		0.45		0.27		0.51		0.27		0.51	
	HIGH SCENARIO	**0.35**		**0.77**		**0.43**		**0.96**		**0.57**		**0.85**		**0.69**		**1.06**	
Biochar Global CCS potential (Gt CO_2-eq)	Low scenario - Sewage + Manure	0.00		0.00		0.16		0.16		0.00		0.00		0.16		0.16	
	Low scenario - OFMSW	0.27		0.27		0.27		0.27		0.27		0.27		0.27		0.27	
	Low scenario - Lignocellulosics	0.05		0.05		0.05		0.05		0.05		0.05		0.05		0.05	
	LOW SCENARIO	**0.32**		**0.32**		**0.48**		**0.48**		**0.32**		**0.32**		**0.48**		**0.48**	
	High scenario -Sewage + Manure	0.00		0.00		0.73		0.73		0.00		0.00		0.73		0.73	
	High scenario - OFMSW	0.30		0.30		0.30		0.30		0.30		0.30		0.30		0.30	
	High scenario - Lignocellulosics	0.24		0.24		0.24		0.24		0.24		0.24		0.24		0.24	
	HIGH SCENARIO	**0.54**		**0.54**		**1.27**		**1.27**		**0.54**		**0.54**		**1.27**		**1.27**	
Global CCUS potential (Gt CO_2-eq)	LOW SCENARIO	**0.40**		**0.52**		**0.58**		**0.72**		**0.46**		**0.54**		**0.65**		**0.75**	
	HIGH SCENARIO	**0.90**		**1.31**		**1.70**		**2.22**		**1.11**		**1.39**		**1.96**		**2.33**	
N required for SCP production (Mt)	LOW SCENARIO	6.57		12.60		8.05		15.75		8.98		13.42		11.00		16.87	
	HIGH SCENARIO	27.24		49.47		33.85		63.55		36.13		52.49		45.17		67.88	
NH_3-N recoverable from Py/Gs (Mt) and amount of SCP nutrient requirement covered (%)	LOW SCENARIO	3.59	54.69%	3.59	28.51%	5.83	72.48%	5.83	37.03%	3.59	40.04%	3.59	26.77%	5.83	53.04%	5.83	34.59%
	HIGH SCENARIO	13.32	48.89%	13.32	26.92%	23.33	68.93%	23.33	36.72%	13.32	36.86%	13.32	25.37%	23.33	51.65%	23.33	34.37%
Total P available from biowaste (Mt) and amount of SCP nutrient requirement covered (%)	LOW SCENARIO	0.62	106.40%	0.62	55.46%	2.28	316.74%	2.28	161.81%	0.62	77.89%	0.62	52.08%	2.28	231.77%	2.28	151.15%
	HIGH SCENARIO	2.65	108.79%	2.65	59.91%	10.03	331.95%	10.03	176.81%	2.65	82.03%	2.65	56.45%	10.03	248.74%	10.03	165.53%

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