Electronic Supplementary Material (ESI) for Environmental Science: Advances.
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Integrated chemical and biochemical technology to produce biogas with reduced ammonia content from municipal biowaste. Validating lab-scale research in real operational environment

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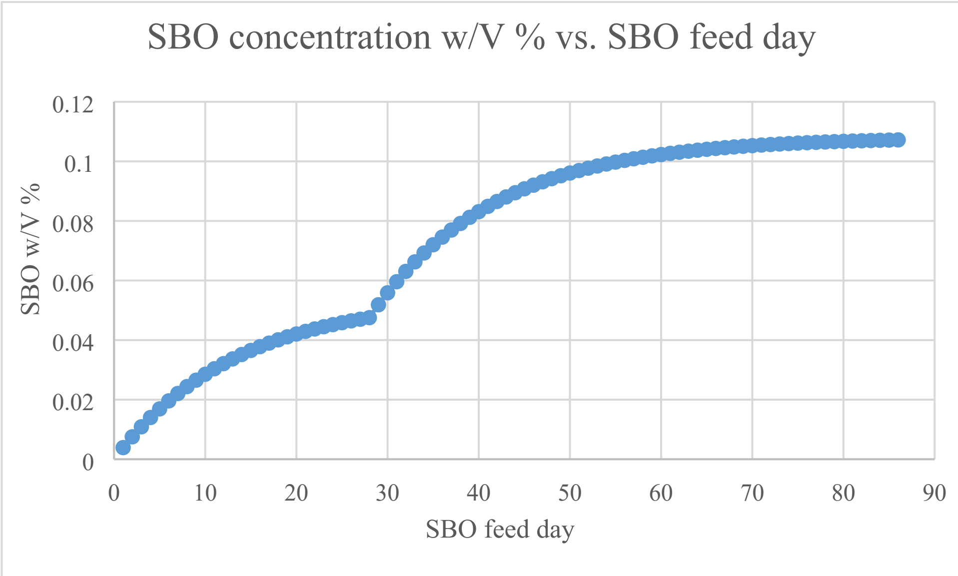
Compost				SBO
Type/Producer/ Country/	Season Year	Pristine Biowaste[a] % w/w	C/N w/w[b]	C/N w/w[b]
CV/OT/GR	Winter 2017-18	WC 48, OM 40, GR 4, L 4, SW 4	19.6±1.2a	14.1±1.2a
CV/OT/GR	Winter-Spring 2018	WC 55, OM 43, GR 2	18.9±1.4a	9.98±1.23b
CV/OT/GR	Spring-Summer 2018	WC 31, OM 47, GR 11, L 4, SW 7	22.2±1.5a	7.12±1.30b
CV/OT/GR	Autumn 2018	WC 56, OM 34, GR 7, L 2, SW 1	19.6±1.4a	15.6±0.8a
CVD/OT/GR	Spring-Summer 2019	GR 67, RFD 33	11.9±0.1a	ND
CVD/OT/GR	Summer-Autumn 2019	GR 67, RFD 33	12.3±0.9a	ND
CVD/OT/GR	Autumn 2019 Winter 2020	GR 67, RFD 33	14.1±0.8a	ND
CVD/OT/GR	Winter-Spring 2020	GR 67, RFD 33	14.3±0.9a	ND
CV/SBLA/CY	Summer-Autumn 2017	GR 100	30.5±1.4e	ND
CV/SBLA/CY	Autumn 2017 Winter 2018	GR 100	9.65±0.16a	9.60±0.45a
CV/SBLA/CY	Spring 2018	GR 100	20.5±0.1b	16.7±1.0c
CV/SBLA/CY	Summer 2018	GR 100	16.5±0.1c	15.9±0.6c
CV/SBLA/CY	Autumn 2018	GR 100	17.3±0.1d	13.5±0.5bc
CVD/SBLA/CY	Winter 2019	GR 67, RFD 33	14.6±0.3a	13.3±0.5b
CVD/SBLA/CY	Spring 2019	GR 67, RFD 33	12.0±0.1b	11.3±0.4a
CVD/SBLA/CY	Summer 2019	GR 67, RFD 33	11.3±0.0c	15.7±0.6c
CVD/SBLA/CY	Autumn 2019	GR 67, RFD 33	9.35±0.1d	ND
CVD/ACEA/IT	Summer-Autumn 2017	MGR 67, MFD 33	9.76±0.16a	8.88±0.40a
CVD/ACEA/IT	Autumn 2017-Winter 2018	MGR 67, MFD 33	11.5±0.5b	10.21±0.6ab
CVD/ACEA/IT	Winter-Spring 2018	MGR 67, MFD 33	11.8±0.6b	9.7±0.5a

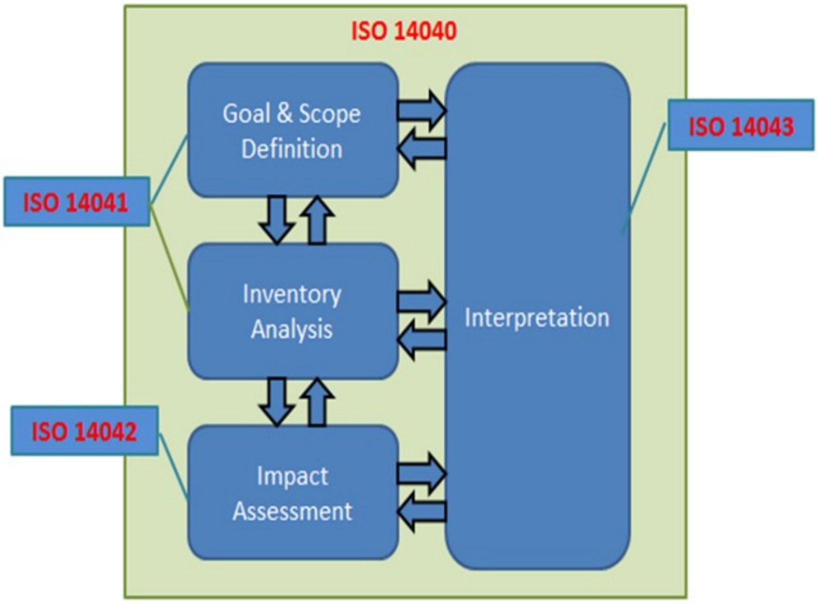
Supplementary Table 1: Composts produced by ACEA, OT and SBLA in different seasons and years using various local pristine biowaste, and SBO manufactured by ACEA employing all types of compost generated.

CVD/ACEA/IT	Spring-Summer 2018	MGR 67, MFD 33	12.0±0.7b	10.2±0.5ab
CVD/ACEA/IT	Summer-Autumn 2018	MGR 67, MFD 33	11.1±0.5ab	9.37±0.4a
CVD/ACEA/IT	Winter 2019	MGR 67, MFD 33	11.2±0.2ab	10.3±0.3ab
CVD/ACEA/IT	Spring 2019	MGR 67, MFD 33	9.30±0.16a	8.21±0.2a
CVD/ACEA/IT	Summer 2019	MGR 67, MFD 33	10.2±0.15ab	8.88±0.3a
CV/ACEA/IT	Summer-Autumn 2018	MGR 100	14.1±0.8a	12.0±0.1a
CV/ACEA/IT	Winter 2019	MGR 100	15.9±0.2b	14.9±0.3c
CV/ACEA/IT	Spring 2019	MGR 100	18.2±1.4c	18.1±0.5d
CV/ACEA/IT	Summer 2019	MGR 100	14.5±0.1ab	13.2±0.1b

[a] WC (wood chips), OM (olive mill waste), GR (gardening residues), L (leaves), SW (saw dust), RFD (restaurants food waste anaerobic digestate), MGR (municipal private gardening and public park trimmings from separate source collection), MFD (municipal food waste anaerobic digestate). [b] Statistical comparison was performed for groups of values regarding the same type of compost or SBO manufactured by the same producer over different seasons. Thus, within each column and for each type of compost and SBO prepared by the same producer over different seasons, values followed by different letters are significantly different at a level of $p<0.01$.



Supplementary Fig. 1: CVD SBO concentration in reactor B during the fermentation trials of ACEA.



Supplementary Fig. 2: The LCA approach according to the ISO 14040 series.

Supplementary Table 2: Industrial water withdrawal, total water withdrawal, net living wage, net salary, and CO_2 emissions in each country of EU-27.

	Industrial water	Total water	Net Living	Net minimum	Working hours	CO_2 emissions

	withdrawal (m³/y)	withdrawal (m³/y)	Wage (€/month)	wage (€/month)	(h/week)	(kg/capita)
Austria	2.70E+09	3.49E+09	983.50	N.A.	36.5	6,870
Belgium	3.21E+09	3.99E+09	957.00	1,216	37.2	8,330
Bulgaria	3.94E+09	5.66E+09	662.00	202	40.7	5,870
Croatia	1.84E+08	7.15E+08	703.04	370	39.6	3,970
Cyprus	1.70E+07	3.11E+08	841.00	N.A.	39.3	5,260
Czech Republic	9.67E+08	1.63E+09	498.64	408	40.1	9,170
Denmark	3.29E+07	7.41E+08	N.A.[a]	N.A.[a]	33.5	5,940
Estonia	1.72E+09	1.79E+09	571.50	482	38.2	14,850
Finland	1.42E+09	6.56E+09	1,064.50	N.A.	36.8	8,660
France	1.82E+10	2.64E+10	1,273.50	1,386.00	37.3	4,570
Germany	1.98E+10	2.44E+10	1,116.50	1,102.00	34.9	8,890
Greece	2.08E+08	1.12E+10	703.00	578	42.0	6,180
Hungary	3.36E+09	4.50E+09	399.93	296	39.6	4,270
Ireland	5.10E+07	7.57E+08	1,589.00	1,509.00	36.5	7,310
Italy	7.70E+09	3.42E+10	896.50	N.A.	37.2	5,270
Latvia	2.52E+07	1.81E+08	653.50	314	38.9	3,450
Lithuania	6.97E+07	2.59E+08	589.00	361	38.6	4,380
Luxembourg	1.60E+06	4.56E+07	1,592.00	1,687.00	37.6	17,360
Malta	1.00E+06	6.38E+07	1,017.00	571	38.9	5,400
Netherlands	1.47E+10	1.61E+10	985.50	1,430.00	30.4	9,920
Poland	7.04E+09	1.01E+10	402.71	353	40.4	7,520
Portugal	1.50E+09	9.15E+09	711.50	587	39.5	4,330
Romania	4.23E+09	6.77E+09	324.35	251	39.6	3,520
Slovakia	2.31E+08	5.56E+08	449.00	397	40.0	5,660
Slovenia	7.58E+08	9.31E+08	783.50	642	39.2	6,210
Spain	5.97E+09	3.12E+10	821.00	733	37.7	5,030
Sweden	1.35E+09	2.38E+09	1,304.55	N.A.[a]	36.4	4,480
Average	**3.68E+09**	**7.56E+09**	**842**	**732**	**37.1**	**6,766**

[a]Not available

Supplementary Table 3: Indicators of living wage (LW), minimum wage (MW), level of facility water use (FWU) in industrial sector and in total for the SBO production process at ACEA, SBLA and OT industrial sites. Data given as ratios of values for the country of ACEA, SBLA and OT to the values for each of the other EU countries.

	ACEA (Italy)				
	Living wage[a]	Minimum wage[a]	Level of facility water use, sector	Level of facility water use, country	Relative contribution of gaseous emissions (GHG)
Austria	3.46	N.A.[b]	0.000099%	0.000076%	0.000332%
Belgium	3.55	2.80	0.000083%	0.000067%	0.000274%
Bulgaria	5.14	16.83	0.000068%	0.000047%	0.000389%
Croatia	4.84	9.19	0.001446%	0.000372%	0.000575%

Cyprus	4.04	8.33	0.015653%	0.000856%	0.000434%
Czech Republic	6.82	N.A.[b]	0.000275%	0.000163%	0.000249%
Denmark	N.A.	N.A.[b]	0.008088%	0.000359%	0.000384%
Estonia	5.95	7.05	0.000155%	0.000149%	0.000154%
Finland	3.19	2.45	0.000188%	0.000041%	0.000264%
France	2.67	N.A.[b]	0.000015%	0.000010%	0.000500%
Germany	3.05	3.09	0.000013%	0.000011%	0.000257%
Greece	4.84	5.88	0.001277%	0.000024%	0.000370%
Hungary	8.50	11.49	0.000079%	0.000059%	0.000535%
Ireland	2.14	2.25	0.005218%	0.000352%	0.000312%
Italy	3.79	N.A.[b]	0.000035%	0.000008%	0.000433%
Latvia	5.20	10.83	0.010560%	0.001469%	0.000662%
Lithuania	5.77	9.42	0.003818%	0.001027%	0.000521%
Luxembourg	2.14	2.02	0.166313%	0.005836%	0.000132%
Malta	3.34	5.95	0.266100%	0.004171%	0.000423%
Netherlands	3.45	2.38	0.000018%	0.000017%	0.000230%
Poland	8.44	9.63	0.000038%	0.000026%	0.000304%
Portugal	4.78	5.79	0.000178%	0.000029%	0.000527%
Romania	10.48	13.55	0.000063%	0.000039%	0.000649%
Slovakia	7.57	8.56	0.001151%	0.000478%	0.000403%
Slovenia	4.34	5.30	0.000351%	0.000286%	0.000368%
Spain	4.14	4.64	0.000045%	0.000009%	0.000454%
Sweden	2.61	N.A.[a]	0.000198%	0.000112%	0.000510%
Average	**1.38**	**4.64**	**0.01783%**	**0.000596%**	**0.00039%**

SBLA (Cyprus)					
	Living wage[a]	Minimum wage[a]	Level of facility water use, sector	Level of facility water use, country	Relative contribution of gaseous emissions (GHG)
Austria	2.42		0.00010%	0.000076%	0.000013%
Belgium	2.49	1.96	0.00008%	0.000067%	0.000011%
Bulgaria	3.60	11.78	0.00007%	0.000047%	0.000015%
Croatia	3.39	6.43	0.00145%	0.000372%	0.000022%
Cyprus	2.83		0.01565%	0.000856%	0.000017%
Czech Republic	4.77	5.83	0.00028%	0.000163%	0.000010%
Denmark			0.00809%	0.000359%	0.000015%
Estonia	4.16	4.94	0.00015%	0.000149%	0.000006%
Finland	2.24		0.00019%	0.000041%	0.000010%
France	1.87	1.72	0.00001%	0.000010%	0.000019%

Germany	2.13	2.16	0.00001%	0.000011%	0.000010%
Greece	3.39	4.12	0.00128%	0.000024%	0.000014%
Hungary	5.95	8.04	0.00008%	0.000059%	0.000021%
Ireland	1.50	1.58	0.00522%	0.000352%	0.000012%
Italy	2.65		0.00003%	0.000008%	0.000017%
Latvia	3.64	7.58	0.01056%	0.001469%	0.000026%
Lithuania	4.04	6.59	0.00382%	0.001027%	0.000020%
Luxembourg	1.49	1.41	0.16631%	0.005836%	0.000005%
Malta	2.34	4.17	0.26610%	0.004171%	0.000016%
Netherlands	2.42	1.66	0.00002%	0.000017%	0.000009%
Poland	5.91	6.74	0.00004%	0.000026%	0.000012%
Portugal	3.35	4.05	0.00018%	0.000029%	0.000020%
Romania	7.34	9.48	0.00006%	0.000039%	0.000025%
Slovakia	5.30	5.99	0.00115%	0.000478%	0.000016%
Slovenia	3.04	3.71	0.00035%	0.000286%	0.000014%
Spain	2.90	3.25	0.00004%	0.000009%	0.000018%
Sweden	1.82		0.00020%	0.000112%	0.000020%
Average	**3.34**	**4.91**	**0.01783%**	**0.000596%**	**0.000015%**

OT (Greece)					
	Living wage[a]	Minimum wage[a]	Level of facility water use, sector	Level of facility water use, country	Relative contribution of gaseous emissions (GHG)
Austria	1.42		0.00010%	0.000076%	0.00135%
Belgium	1.46	1.15	0.00008%	0.000067%	0.00111%
Bulgaria	2.11	6.91	0.00007%	0.000047%	0.00157%
Croatia	1.99	3.77	0.00145%	0.000372%	0.00233%
Cyprus	1.66		0.01565%	0.000856%	0.00176%
Czech Republic	2.80	3.42	0.00028%	0.000163%	0.00101%
Denmark			0.00809%	0.000359%	0.00155%
Estonia	2.44	2.90	0.00015%	0.000149%	0.00062%

Finland	1.31		0.00019%	0.000041%	0.00107%
France	1.10	1.01	0.00001%	0.000010%	0.00202%
Germany	1.25	1.27	0.00001%	0.000011%	0.00104%
Greece	1.99	2.42	0.00128%	0.000024%	0.00149%
Hungary	3.49	4.72	0.00008%	0.000059%	0.00216%
Ireland	0.88	0.93	0.00522%	0.000352%	0.00126%
Italy	1.56		0.00003%	0.000008%	0.00175%
Latvia	2.14	4.45	0.01056%	0.001469%	0.00268%
Lithuania	2.37	3.87	0.00382%	0.001027%	0.00211%
Luxembourg	0.88	0.83	0.16631%	0.005836%	0.00053%
Malta	1.37	2.45	0.26610%	0.004171%	0.00171%
Netherlands	1.42	0.98	0.00002%	0.000017%	0.00093%
Poland	3.47	3.96	0.00004%	0.000026%	0.00123%
Portugal	1.96	2.38	0.00018%	0.000029%	0.00213%
Romania	4.30	5.56	0.00006%	0.000039%	0.00263%
Slovakia	3.11	3.52	0.00115%	0.000478%	0.00163%
Slovenia	1.78	2.17	0.00035%	0.000286%	0.00149%
Spain	1.70	1.90	0.00004%	0.000009%	0.00184%
Sweden	1.07		0.00020%	0.000112%	0.00206%
Average	**1.96**	**2.88**	**0.01783%**	**0.000596%**	**0.00160%**

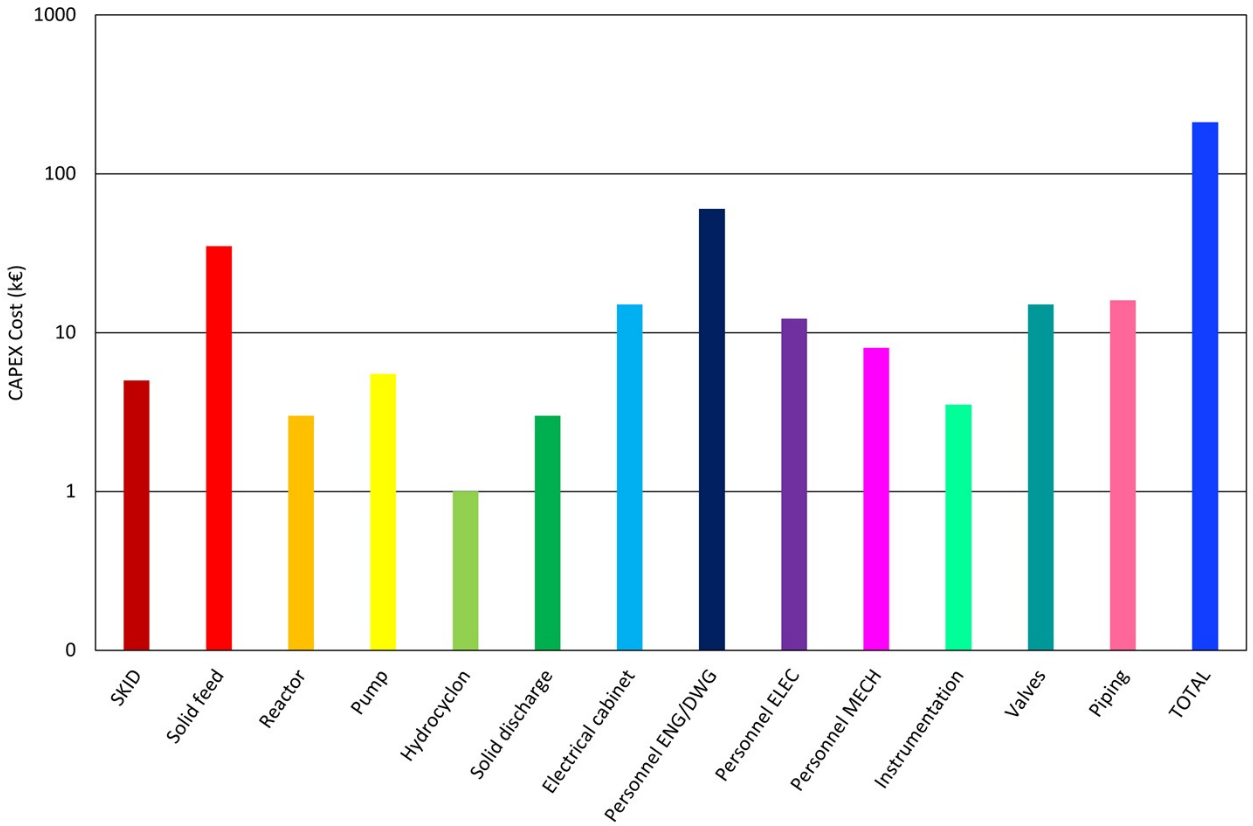
[a]k€/month. [b]Not available

Supplementary Table 4: Calculations of total cost for ammonia nitrogen abatement (C, €/kg NH_3-N) in the cases of ACEA, OT and SBLA, based on the NH_3-N concentrations determined in reactors A and B.

Case[a]	Operational site	Data source[b]	NH_3-N (mg/L) in A	NH_3-N (mg/L) in B	C (€/kg NH_3-N)[c]
1	ACEA Full-scale reactor (2560 m^3)	Fig. 4, day 57[d]	1103.2	498.8	0.60
2	ACEA Full-scale reactor (2560 m^3)	Main text for CV day 33	1018.9	737.4	2.18
3	OT Pilot-reactor (480				

	L)				
4	OT Pilot-reactor (480 L)	Fig. 5, day 20	761	553	3.47
5	OT Pilot-reactor (480 L)				
6	OT Pilot-reactor (480 L)	Fig. 5 day 20	723	571	4.75
7	SBLA Pilot-reactor (400 L)	Fig. 8, day 12	1120.8	775.2	0.52
8	SBLA Pilot-reactor (400 L)	Fig. 8, day 14	1359	799.2	1.29
9	SBLA Pilot-reactor (400 L)	Fig. 8, day 14	1106.6	859.2	0.73
10	SBLA Pilot-reactor (400 L)	Fig. 8, day 14	1874.9	604.8	0.56

[a]Case numbers reported in Table 5. [b]Figs. 4-8 in the main body of the manuscript. [c]Calculations of ammonia abatement cost (C, €/kg ammonia abated) according to equations (1) and (2), $C = 0.0361\ Y/X$ (1) and $X = V\ (N_B - N_A)$ (2), where 0.0361 constitutes the production cost of the 10% SBO solution in €/kg, Y is the total weight in kg of 10% SBO solution added in reactor B, X is the total weight of ammonia in kg abated in reactor A, N_B and NA comprise the concentrations of ammonia in reactors B and A, and V is the total volume of reactor B. There are no data provided for cases 3 and 5, since N_B and N_A values were not significantly different. [d]Liquid digestate



Supplementary Fig. 3: Detailed capital expenditure.

Assessment of socio-economic impact (S-LCA) on local economy and population

Green chemistry (GC) has evolved into the more holistic green and sustainable chemistry (GSC) concept,[1] aiming to improve integration of the social and economic dimensions of sustainability. Thus, LifeCycle Sustainability Assessment (LCSA) represents a key assessment framework considering all dimensions of sustainability in a life cycle thinking based assessment, thereby integrating E-LCA, S-LCA and LCC. Social analysis (S-LCA) constitutes one of the three pillars of sustainability assessment. There is no definite unique model protocol to perform S-LCA. Guidelines are available and continuously updated to establish the specific evaluation tool more comprehensive and reliable along the development of the biobased economy.[2, 3] Several critical issues often occur in S-LCA studies, including the availability of high quality data sets and the implementation of consensual impact indicators. A current objective of LCSA is to overcome these limitations and achieve complementarity of S-LCA with environmental (E-LCA) and Life cycle costing (LCC) analyses.[4]

S-LCA analysis was undertaken here to complement E-LCA and LCC analyses, evaluating potential social impacts, which may not occur due to unforeseen circumstances. The main objective was to form a basis aiming to build a more comprehensive prospective approach, linking the three types of impacts derived from SBO production and consumption. At the present state-of-the-art, based on the experimental technical data obtained from the three ACEA, SBLA and OT case studies, several indicators could be estimated to evaluate the social effects of potential implementation of processes 1 and/or 2 in the European context. Indicators were associated to workers and local community stakeholders as primary target actors directly affected by the negative and/or positive impact of the new processes 1 and 2. Notably, the study only addressed the social effects caused by the organizations of each case study delivering processes 1 and 2, as well as SBO. Other stakeholder categories[2, 3] (such as consumers, local public authorities, NGO leaders, etc.) along the supply-chain of processes 1 and 2 were not considered. These will be taken into account upon implementation of the real industrialisation of the processes and product envisioned. The S-LCA reported was limited to the validation of processes 1 and 2 in the real operational conditions of ACEA, SBLA and OT.

Supplementary Tables 5 and 6 present the selected stakeholder categories, related indicators and equations to calculate the indicators of the S-LCA study. The indicators evaluated across the stakeholder categories selected were calculated using information derived from experimental results (representing the primary data) and accessible information relevant to the European context. Indicators related to global sector conditions were additionally evaluated offering a perspective of the social impact caused by the industrial sector in Europe. Indicators' normalization to European conditions and the assessment were carried out considering a risk scale according to the Product Social Impact Life Cycle Assessment (PSILCA) database developed by Greendelta.[5]

Supplementary Table 5 Social indicators used in the study to evaluate the social impact of the approach demonstrated.

Stakeholder	**Subcategory**	**Indicator**
Workers	Children labour	Children in employment, total (5 – 17 years)
	Fair salary	Living wage, per month
		Minimum wage, per month
	Working time	Hour of work per employee
Local community	Local employment	Job generation
	Access to material resources	Level of facility water use (related to the industrial sector)
		Level of facility water use (related to actual renewable resources)
	Safe and healthy living conditions	Relative contribution of GHG emissions

Supplementary Table 6 Explanation of social indicators used to perform social analysis.

Indicator	Equation	Symbol	Units
Children in employment, total (5 – 17 years)	$CLindustrial = \frac{Children\ in\ employment}{Total\ in\ the\ country} \times 100$	CL: Children labour	-
Living wage, per month	$LW = \frac{Total\ salary\ per\ month}{Living\ wage\ per\ month} \times 100$	LW: Living wage	%
Minimum wage, per month	$MW = \frac{Total\ salary\ per\ month}{Minimum\ wage\ per\ month} \times 100$	MW: Living wage	%
Hour of work per employee	-	WH: Work hours	h/employee
Job generation	-	N employees	-
Level of facility water use, sector	$FWU_{sector} = \frac{Wprocess + Wcooling}{Windustrial\ water\ withdrawal} \times 100$	FWU: Facility water use	%
Level of facility water use, country	$FWU_{total} = \frac{Wprocess + Wcooling}{Wtotal\ water\ withdrawal} \times 100$	W: Volume flow of water (m^3/year)	
Relative contribution of gaseous emissions	$RCGE = \frac{CO_{2-eq}\ released}{CO_{2-eq}\ in\ each\ country} \times 100$	$RCGE$: Relative contribution to GHG	%

Workers category. The social impact imputed to the workers' stakeholder category was evaluated considering child labor, fair salary and working time as subcategories. Each subcategory was assessed through calculation of the four indicators presented in Table 5. The first indicator referred to the estimation of total children in employment. The biorefineries under development for construction in EU-27 should be aligned with Directive 94/33/EC regarding the protection of young people at work. The Directive's main objective is to prohibit the employment of children, including as the only exception children's work under certain conditions for cultural, artistic, sporting or advertising activities. Employment in the industrial sector is strictly forbidden and consequently the specific indicator was zero in all case studies.[6]

The second subcategory (fair salary) involved calculation of the monthly salary of workers in the chemical industry and comparison against the living and minimum wages of the reference country. Living wage describes the adequate living standard of a country, including costs for nutritious food, water, shelter, clothing, education, healthcare, transport and communication, while the minimum wage constitutes a national legally binding obligation on employers, defined as the minimum amount of remuneration that an employer is required to pay. The information relevant to living and minimum wages in EU-27 was extracted from WageIndicator.org,[7] where values are calculated based on living cost prices.

The third working time subcategory considered the number of working hours per employee as indicator, which was calculated considering the duration of plant operation and the working time for each worker. It was assumed that the industrial plant operated 24 h/d, 7 d/week, 3 shifts/d and 7920 h per year, while a single worker worked approximately 8 h/shift, 5 d/ week and 47 weeks/year considering vacations and sick leave allowances. Thus, each worker completed 235 shifts/year. Considering that at least one worker should be present in the plant at any time throughout the year, 4.5 workers should be employed, working 37 h per week (24 h/d × 7 d/week / 4.5 workers), which is relevant to the working hours in each county of EU-27.[8]

Local community category. The social impact caused to the local community via implementation of MBW biorefineries was evaluated considering three subcategories related to local employment, use of natural resources and healthy living conditions. The local employment subcategory assessed job generation occurring due to the construction of the industrial plant. The operating labor was estimated by multiplying 4.5 (derived from the assumption analyzed in the "Workers" section) with NOL, e.g. the summary of workers required for all units of equipment of each biorefinery. Specifically, the estimation of the number of workers of each biorefinery was based on the methodology developed by Ulrich.[9] The specific methodology allowed estimating the number of workers required per shift for proper operation of each unit of equipment and depended on the number of units for each type of equipment and the annual production capacity selected. For each of the three ACEA, OT and SBLA cases, two new job positions were calculated (supplementary Table 7) representing the operating labor and excluding any supporting or supervisory staff. Along with the jobs created by producing greener chemicals (e.g. SBO), additional jobs could be created via replacement of fossil chemical feedstocks with renewable raw materials (e.g. MBW).

Supplementary Table 7 Data required for estimation of the social indicator in each case[a]

	ACEA	SBLA	OT
CL in the industry	0	0	0
Gross salary (S, €/month)	3,400	2,380	2,327
Net salary (S, €/month)	2,040	1,428	1,396
N employees	2	2	2
WH total (h/week)	37	37	37
WP (m^3/y)	2,661	2,661	2,661
WC (m^3/y)	0	0	0
CO_2-eq (kg/capita) released	0.016	0.00089	0.093
CO_2-eq (kg/capita) saved	0.0064	0.00073	0.036

[a]Data for child labour (CL), salary (S), number (N) of employees, working hours (WH), process water (WP), cooling water (WC), and the equivalent of carbon dioxide (CO_2-eq) for the cases of ACEA, SBLA and OT.

The second subcategory (access to material resources) evaluated whether the access of local communities to material resources was restricted because of commercial or industrial activities in their regions. Implementation of a new facility increased the demand for natural resources, which could lead to their depletion and conflict between different actors over these resources. The specific subcategory involved calculating the level of facility water use, which was evaluated as the ratio of the mass flow of water used in the biorefinery (cooling water + process water) over the total water employed in the industrial sector and available in the country. The AQUASTAT database, constructed by the Food and Agriculture Organization of the United Nations (FAO), was used to determine the value of total industrial water withdrawal and total water withdrawal.[10] Industrial water withdrawal referred to the annual quantity of self-supplied water withdrawn for industrial use, which was not connected to the public distribution network. The specific water supply could include water from primary renewable and secondary freshwater resources, as well as water from over-abstraction of renewable groundwater or withdrawal from fossil groundwater, direct use of agricultural drainage water, direct use of (treated) wastewater, and desalinated water. However, the term total water withdrawal described the annual quantity of water withdrawn for agricultural, industrial, and municipal purposes.

The safe and healthy living conditions subcategory included comparison of the GHG emissions of each biorefinery against the overall GHG emissions of the country selected. Information about the GHG emissions of EU-27 was derived from the Carbon Dioxide Information Analysis Center.[11] Although the specific LCA indicated that processes 1 and 2 did not significantly affect GHG (kg $CO_{2\text{-eq}}/kg_{product}$) emissions, the methodology demonstrated significant effect on NH_3 reduction. The analysis of social impacts for the three different cases (ACEA, SBLA, OT) was based on data inputs derived from LCA. Table 7 provides the data required for the estimation of the social indicator in each case (ACEA, SBLA, OT), while supplementary Table 8 summarizes the results relevant to social indicators.

Supplementary Table 8 Social indicators[a] results for the case studies of ACEA, SBLA and OT.

	ACEA	SBLA	OT
CL in the industry	0	0	0
LW per month (ratio)	228%	170%	199%
MW per month (ratio)	N.A.[b]	N.A.[b]	2.42
HWE	37	37	37
FWU, sector	0.000035%	0.016%	0.001%
FWU, country	0%	0%	0%
GHG	0.000433%	0.000017%	0.0017%

[a]Child labour (CL), living wage (LW), minimum wage (MW), level of facility water use (FWU), hour of work per employee (HWE) per week, relative contribution of gaseous emissions (GHG).
[b]Not available

The monthly salary considered for the evaluation (Table 7) was estimated by taking into consideration the median hourly gross earnings that Eurostat reports as well as the removal of taxes aiming to estimate the net salary. Specifically, the median hourly gross earnings inEU-27 comprise 13.54 €/h.[12] Herein, the hourly gross earnings were equal to 15.72 €/h, given that the specific value corresponded to the average hourly gross earning of the countries holding the highest industrial activity in Europe.[13] Thus, the net salary was estimated by removing the amount of taxes which was considered as 40% of the gross salary. Moreover, the lack of values for the minimum wage in Austria, Denmark, Finland, Cyprus, Italy and Sweden occurred because these countries do not have a minimum wage set by the government (collective bargaining agreements effective, instead of minimum wage).[14]

The child labour indicator was considered as zero (Table 8), given that child employment is forbidden in the European Union. The indicators of living wage (LW) and minimum wage (MW) were evaluated for the subcategory fair salary, by comparing the salary considered for the labour of the SBO production process to the LW and MW of EU-27 countries as well as to the average wage. ESI Table 2† reports the social indicators' values in EU-27. The HWE value of the SBO process in Table 10 comprised the average calculated over the HWE of EU-27. Regarding the access to material resources, the level of facility water use (FWU) was evaluated as compared to the water use of the industrial sector and the total available water of EU-27. Supplementary Table 3 demonstrated that the average contributions of water use by ACEA, SBLA and OT accounted for 0.01783%, relative to the total water used in the industrial sector, and 0.000596% of the total water available in each country. The single ACEA, SBLA and OT contributions were equal, due to the assumption that facilities and production capacities were the same in all cases. The single ACEA, SBLA and OT contributions, referred to each of the countries of EU-27, varied significantly due to large differences in the industrial activities of each country. For example, Luxembourg and Malta indicate very low industrial activity and therefore ACEA, SBLA and OT FWU percentages were quite high. Countries that include high industrial activity, usually consume elevated amounts of water for industrial use. Thus, relative to the total industrial water consumption in EU, the percentages for various countries comprised Germany 28%, Italy 16%, France 12%, Spain 8% and Poland 5%. Regarding the specific countries, the consumptions of ACEA, SBLA and OT were equal or below 0.0001%. ESI Table 3† additionally reports the relative contributions of GHG emissions due to the SBO production process, demonstrating that the average GHG emissions were 0.0016% in the case of OT, 0.000015% in SBLA and 0.00039% in ACEA. However, LCA shows that remarkable environmental benefits could be obtained from ammonia reduction through the SBO assisted fermentation process 2.

Supplementary Table 9 The social indicator for Italy, Greece, and Cyprus, countries where the companies of ACEA, SBLA, and OT are located, and risk scales adapted to European conditions.

Indicator	ACEA	SBLA	OT	Risk table	Units	Reference
Total children in employment (5–17 years)	Northern, Southern and Western Europe 0.5 Eastern Europe 4.6			1) 0-7.5 2) 7.5-13.3 3) 13.3-19.1 4) 19.1-29.1 5) 29.1-32.0	(%)	39
	0	0	0			
Country LW/EU27 average LW *Case net salary/ Country LW	Italy 106.5 *Case 403.8	Cyprus 99.9 * Case 334.5	Greece 83.5 * Case 196.2	1) 155-190 2) 121-155 3) 78-121 4) 48-78 5) 38-48	(%)	35
Minimum wage *Case net salary/ EU27 average MW)	Italy N.A * Case 464	Cyprus N.A. * Case 325	Greece 78.9 * Case 196.2	1) 196-231 2) 151-196 3) 100-151 4) 70-100 5) 20-70	(%)	35
Level of facility water use (FWU), sector	Italy 209.4 * Case 0.0	Cyprus 0.5 * Case 0.0	Greece 5.6 * Case 0.0	1) 0-100 2) 100-200 3) 200-300 4) 300-400 5) 400-500	(%)	38
Level of facility water use (FWU), country	Italy 452.2 * Case 0.0	Cyprus 4.1 * Case 0.0	Greece 148.6 * Case 0.0	1) 0-100 2) 100-200 3) 200-300 4) 300-400 5) 400-500	(%)	38
Relative contribution of gaseous emissions (GE)	Italy 77.82 * Case 0.0	Cyprus 77.75 * Case 0.0	Greece 91.35 * Case 0.0	1) 0-50 2) 50-100 3) 100-150 4) 150-200 5) 200-250	(%)	40

1) Very low risk, 2) low risk, 3) medium risk, 4) high risk, and 5) very high risk.

Supplementary Table 9 presents the results obtained for the social indicators and their comparison against the risk level index of the social indicators estimated for the countries (Italy, Greece, and Cyprus) where ACEA, SBLA, and OT are located. The specific values constitute a measure of the negative impact that implementation of SBO production to industrial level could bring to the local economy and population. The risk levels in Table 9 were given as ranges encompassing the minimum and maximum indicator values within EU countries according to the references cited in the Table. Regarding the child labor category levels were set within the global context. Thus, in Northern, Southern and Western Europe, as well as Eastern Europe, the risk of child labor was very low, representing 0.5% and 4.6% of the total people in employment, respectively. Regarding the cases of ACEA, SBLA and OT child labor was considered as zero. The living wage (LW) indicator constitutes the ratio of a specific country's LW to the average EU-27 LW. The risk in Italy, Greece, and Cyprus indicated medium risk as compared to other countries in the European context. However, the LW indicator for each study case was estimated as the ratio of the case's salary over the LW value corresponding to the country where the company was located. Thus, regarding ACEA's LW, * Case 403.8 (Table 9) corresponded to the ratio of the salary in ACEA over Italy's living wage. The results show very low risk for the three cases of ACEA, SBLA and OT, demonstrating that the salary used in the techno-economic evaluation of each study was higher than the country's living wage. The minimum wage indicator constitutes the lowest wage that a full-time worker could be paid according to the specific law in each country. The risk factor in this case constitutes the LW/MW ratio. Regarding ACEA, SBLA and OT, the specific indicator was calculated as the ratio of the salary in each study case over the country's MW. Very low risk occurred exhibiting that salaries were higher in the three companies of this work as compared to the minimum wage in each country.

Sector FWU comprised the quantity of water consumed for the production of SBO implemented in the above countries, as compared to other local industrial activities, indicating the risk for potential conflict between SBO production and local industrial activities over water resources. Thus, sector FWU determined that the risk of SBO production accounted for a large share of industrial water withdrawal. Country FWU indicated the pressure of the industrial implementation of SBO on water resources, predicting the risk that SBO production could negatively affect the local community's quality of life. The GE factor indicated the health risk imposed due to gaseous emissions from the implemented of the SBO production process, as compared to the total local emission.

Results in Table 9 indicate low-medium risk for the indicators measured, apart from the country FWU in ACEA, which included a high level. Moreover, the security of water supply has become a high-priority issue in many countries. However, considering that ACEA could use the clean water produced from its urban wastewater treatment facility in process 1 (Fig. 2B), the water supply for SBO production was not considered as a critical risk factor that could negatively impact the SBO production process and local water availability.

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