

Electronic Supplementary Information

Clicking the sustainability: Nobel-awarded copper catalysed azide-alkyne cycloadditions (CuAAC) through Life Cycle Assessments analysis

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1. Methodology

1.1 Goal and scope definition

The main aim of the present LCA study is to evaluate the environmental and human health profile related to a series of synthetic procedures adopted for the preparation of triazoles, through copper-catalyzed azide-alkyne cycloaddition (CuAAC), to disclose which are the components or the procedures that mostly hamper their sustainability. Experimental procedures for the synthesis of the benchmark triazole 1-benzyl-4-phenyl-1,2,3-triazole were extracted from the literature. The five most notable examples in terms of excellent yields, selectivity, and variety of catalysts and conditions were chosen to evaluate their impact through an LCA study.¹⁻⁵

The system boundary was defined using a cradle-to-gate approach, and the functional unit was set to 1 g of the target product. Resource exploitation and emissions to water, air, and soil were shaped by both the extraction and manufacturing of all materials, thereby framing the environmental profile and subsequent human health impacts for each chemical route analyzed.^{6,7}

It was assumed that all processes were conducted at a single site.

Environmental impacts from raw material transportation were accounted for, based on transport distances of 100 km by lorry (>16 t) and 600 km by train. Additionally, the impacts associated with chemical plant infrastructure, including manufacturing facilities and equipment, were incorporated (4.00×10^{-13} unit).

1.2 Inventory analysis

While setting up the LCA analysis, adopting a retrosynthetic strategy, new inventories for several chemicals have been prepared to be utilized in the evaluation. When an existing inventory dataset was available in the literature, it was considered, adjusted according to the provided assumptions, and used for constructing other inventories. General assumptions were made regarding process energy (0.0002 MJ per gram of the compound) and electricity consumption (0.000333 kWh per gram of the compound) for all unavailable compounds that required specific modeling. Given the European Union's statements that the production and use of energy account for over 75% of greenhouse gas emissions across Europe,⁸ the contribution of electricity in the final synthetic steps affording the desired molecule has been intentionally omitted, as it is nearly identical across all the procedures studied. This exclusion from the system boundary has been further motivated by different factors. First, because the reaction is carried out at temperatures close to room temperature, the energy demand associated with stirring can be considered negligible. In addition, DFT calculations reported by Himo and colleagues³ demonstrated that the azide-alkyne cycloaddition is a highly exothermic reaction, releasing approximately 60.8 kcal/mol. Under these conditions, the intrinsic chemical

energy of the reactants represents the main driving force of the process, while external energy inputs play only a marginal role compared with the need to control the spontaneous heat release for safety purposes. Accordingly, the present analysis, primarily focused on atomic efficiency, emphasizes the impact of the chemicals involved, with particular attention to the environmental and human health implications associated with the selection of catalysts, reducing agents, and, most importantly, solvents, whose significant contribution to the environmental footprint of chemical processes is widely recognized. Particularly, the emissions considered, consistent with LCA studies of chemical processes and representing the primary contributors to the associated impacts, were calculated and assumed as follows:⁹⁻¹¹

- 0.20% of volatile input materials were considered to be emitted in the atmosphere as a consequence of the procedural operations;
- 24.50% of the wastewater treatment was presumed to be oxidized and released into the air as CO₂ (in the case of organic materials);
- 65.80% of the organic compounds were retained in the sludge;
- 9.70% was modeled to be discharged into rivers;
- No emissions to the soil were determined, as no agricultural destination for the digested sludge was considered.

Assumptions regarding data gaps and proxies, have been clearly outlined in the corresponding inventory tables. Specifically, the inventory for Polarclean® (*vide infra*) was not newly developed, as an existing one from the literature was used. Finally, to evaluate the absolute impact of the chemical synthesis, the yields of all procedures were standardized to 95%.

1.3 Impact assessment

The impact assessment was performed using SimaPro 9.6 software and the ReCiPe 2016 method, considering 18 impact categories (*Global warming, Stratospheric ozone depletion, Ionizing radiation, Ozone formation, Human health, Fine particulate matter formation, Ozone formation, Terrestrial ecosystems, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity, Water consumption*).¹²

Midpoint impact categories and Endpoint damage areas (*Human health, Ecosystems, and Resources*) were analyzed hierarchically over a 100-year period. Long-term emissions, which

affect scenarios beyond 100 years, were excluded. The results from the various protocols examined are presented and analyzed in Midpoints, with outcomes weighted and normalized in Endpoint damage areas. This enables a comparison of our approach with others using a single indicator as a benchmark for global environmental impact. During this process, Midpoint characterization results are transformed into intermediate units, which are then weighted and normalized to represent the relative impact in millipoints (mPts), reflecting their severity within a global context.

2. LCA Inventory dataset

2.1 Inventories for the reference processes

Table SI-1. Inventory for the Chan et al. procedure¹

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Phenyl acetylene	0.456	0.0009	0.0056	0.0022	0.0150
Benzyl azide	0.595	0.0012	0.0073	0.0029	0.0196
Sodium ascorbate	0.035		0.009	0.0030	0.0230
Copper sulfate	0.011			0.0055	0.0055
Ligand	0.084		0.0210	0.0080	0.0550
tBuOH ^a	9.289	0.0185	2.276	0.9010	6.1120
H ₂ O ^a	5.947	0.0118		5.9350	
Chemical factory	4xE-13 p				

^atBuOH:H₂O 2:1. 0.25M; Isobutanol used instead of tBuOH

Table SI-2. Inventory for the Rostovtsev et al. procedure²

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Phenyl acetylene	0.456	0.0009	0.0056	0.0022	0.0150
Benzyl azide	0.595	0.0012	0.0073	0.0029	0.0196
tBuOH ^a	6.984	0.0140	1.7111	0.6774	4.5955
H ₂ O ^b	120.715	0.2414		120.4736	
Cu(0)	1.49				1.490
Chemical factory	4xE-13 p				

^aIsobutanol used instead of tBuOH; ^bSum of H₂O used as reaction and purification solvent

Table SI-3. Inventory for the Himo et al. procedure³

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Phenyl acetylene	0.456	0.0010	0.0060	0.0020	0.0150
Benzyl azide	0.595	0.0010	0.0070	0.0030	0.0200
Sodium ascorbate	0.088		0.0220	0.0090	0.0580
Copper sulfate	0.011			0.0055	0.0055
tBuOH ^a	6.984	0.0140	1.7110	0.6770	4.5950
H ₂ O ^b	158.515	0.3170		158.1980	
Chemical factory	4xE-13 p				

^aIsobutanol used instead of tBuOH; ^bSum of H₂O used as reaction and purification solvent

Table SI-4. Inventory for the Lal et al. procedure⁴

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Phenyl acetylene	0.456	0.0009	0.0011	0.0004	0.0030
Benzyl azide	0.595	0.0012	0.0015	0.0006	0.0039
CuBr(PPh ₃) ₃	0.021		0.0051	0.0020	0.0138
Ethyl acetate ^a	16.107 ^a	0.0320	3.9460	1.5620	10.5980
Chemical factory	4xE-13 p				

^aAmount assumed**Table SI-5.** Inventory for the Luciani et al. procedure⁵

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Phenyl acetylene	0.456	0.0010	0.0060	0.0020	0.0150
Benzyl azide	0.595	0.0010	0.0070	0.0030	0.0200
Sodium ascorbate	0.090		0.0220	0.0090	0.0590
Copper sulfate	0.004			0.0020	0.0020
Polarclean® ^a	1.453	0.0030	0.3560	0.1410	0.9560
H ₂ O ^b	4.832	0.0100		4.822	
Chemical factory	4xE-13 p				

^aEmissions deriving from the physiological losses during recovery procedure; ^bSum of H₂O used as reaction and purification solvent

2.2 Inventories for the needed compounds in the synthesis approaches that were not available in life cycle databases

Table SI-6. Synthesis of (1,2-dibromoethyl)benzene¹³

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Styrene	0.420	0.0008	0.0062	0.0024	0.0166
Bromine	0.645	0.0013	0.0095 ^a	0.0038	0.0255
Dichloromethane	7.505	0.0150	1.8387	0.7280	4.9383
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aEmitted as Br₂

Table SI-7. Synthesis of phenyl acetylene¹⁴

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
1-(1,2-dibromoethyl) benzene	2.692	0.0054	0.0264	0.0104	0.0709
Sodium hydroxide	0.857			0.0367	0.0367
Ethanol	26.855	0.0537	6.5795	2.6049	17.6706
Dichloromethane	33.909	0.0678	8.3077	3.2892	22.3121
Hexane	205.800	0.4116	50.4210	19.9626	135.4164
Ethyl acetate	5.412	0.0108	1.3259	0.5250	3.5611
Sodium bromide ^a				1.0080	1.0080
Water ^a				0.3520	
Silica gel	50				50
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product**Table SI-8.** Synthesis of sodium azide (NaN₃)¹⁵

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Ethanol ^a	2.829	0.0057	0.5006	0.1982	1.3443
Sodium nitrite	1.171	0.0023			
Sulfuric acid	0.816	0.0016		0.4080	0.4080
H ₂ O	1.905	0.0038		1.9012	
Hydrazine hydrate ^b	0.849				
Sodium hydroxide	0.536			0.2680	0.2680
Tributylamine ^c	0.062	0.0001	0.0152	0.0060	0.0408
Ethanol ^d			0.1918	0.0760	0.5152
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aSum of ethanol used as reaction and purification solvent; ^bHydrazine used instead of hydrazine hydrate; ^cTriethylamine used instead of tributylamine; ^dReaction side product

Table SI-9. Synthesis of benzyl azide¹⁶

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Benzyl chloride	0.960	0.0019	0.0024	0.0009	0.0063
Sodium azide	0.592			0.0202	0.0202
Dimethyl sulfoxide	6.962	0.0139	1.7057	0.6753	4.5810
H ₂ O	63.291	0.1266		63.1646	
Hexane	49.992	0.1000	12.2480	4.8492	32.8945
Magnesium sulfate	10.000			5.0000	5.0000
Sodium chloride ^a				0.2195	0.2195
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product**Table SI-10.** Synthesis of sodium ascorbate¹⁷

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Ascorbic acid	0.889				
Sodium bicarbonate	0.0430			0.0215	0.0215
H ₂ O	0.8890	0.0018		0.8872	
Isopropanol	8.7350	0.0175	2.1401	0.8473	5.7476
H ₂ O ^a				0.0910	
CO ₂ ^a			0.2200		
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product**Table SI-11.** Synthesis of iron (III) nitrate [Fe(NO₃)₃]¹⁸

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Nitric acid	1.578	0.0032			

H ₂ O	0.674	0.0013		0.6727	
Iron pellets	0.795				0.5640
NO ₂ ^a			0.5700 ^b		
H ₂ O ^a				0.2230	
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product; ^bEmitted as NO₂

Table SI-12. Synthesis of prop-2-yn-1-ol¹⁹

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Epichlorohydrin	3.495	0.0070	0.4624	0.1831	1.2418
Fe(NO ₃) ₃	0.012				0.0116
Sodium	2.621			1.7710	
Ammonia (liquid)	16.553	0.0331	3.8984	1.5435	10.4701
Ammonium chloride	5.339			5.3390	
Diethyl ether	10.339	0.0207	2.5331	1.0029	6.8031
Potassium carbonate	0.485			0.0470	0.3191
Succinic acid	0.045		0.0110	0.0044	0.0296
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

Table SI-13. Synthesis of 3-bromoprop-1-yne²⁰

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
prop-2-yn-1-ol	0.596	0.0012	0.0306	0.0121	0.0823
Phosphorous tribromide ^a	1.010	0.0020		0.1232 ^b	0.1232
Toluene	1.490	0.0030	0.3651	0.1445	0.9804
H ₂ O	0.882	0.0018		0.8802	
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				

Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aPCl₃ used as proxy of PBr₃; ^bEmitted as PBr₂OH

Table SI-14. Synthesis of 2-propyn-1-amine²¹

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
3-bromoprop-1-yne	3.457	0.0069	0.3176	0.1257	0.8530
Ammonia (liquid)	30.755	0.0615	7.5350 ^a	2.9832 ^b	20.2368
Sodium amide	2.493			0.6795	0.6795
H ₂ O	5.810	0.0116		5.7984	
Potassium hydroxide	5.810			2.9050	2.9050
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aEmitted as gaseous ammonia; ^bEmitted as ammonium hydroxide

Table SI-15 Synthesis of sodium acetate²²

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Sodium Hydroxide	0.513			0.013	0.0123
Acetic acid	0.772	0.002	0.009	0.004	0.025
H ₂ O	0.513	0.001		0.731 ^a	
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aSum of water initially used and waste side product

Table SI-16. Synthesis of *N*-(prop-2-yn-1-yl)acetamide²³

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
2-propyn-1-amine	0.644	0.0013	0.0189	0.0075	0.0509
Acetic anhydride	1.314	0.0026	0.0644	0.0255	0.1729

Sodium acetate	1.056		0.2586	0.1024	0.6947
H ₂ O	11.700	0.0234		11.6766	
Sodium chloride	4.212			2.1060	2.1060
Dichloromethane	17.290	0.0346	4.2361	1.6771	11.3768
Diethyl ether	2.824	0.0056	0.6919	0.2739	1.8582
Acetic acid ^a			0.1515	0.0600	0.4068
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product

Table SI-17. Synthesis of N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)acetamide²³

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
N-(prop-2-yn-1-yl)acetamide	0.624	0.0012	0.0011	0.0004	0.0030
Benzyl azide	0.856	0.0017	0.0015	0.0006	0.0041
Copper sulfate	0.032			0.0160	0.0160
Ascorbic acid	0.113				
Sodium hydroxide	0.026				
H ₂ O	14.755	0.0295		14.7255	
Ammonia	0.999	0.0020	0.2448 ^a	0.0969	0.6573
Dichloromethane	46.057	0.0921	11.2840	4.4675	30.3055
Diethyl ether	11.726	0.0235	2.8729	1.1374	7.7157
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aEmitted as gaseous NH₃

Table SI-18. Synthesis of (1-benzyl-1H-1,2,3-triazol-4-yl)methanamine (ligand)²⁴

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
N-((1-benzyl-1H-1,2,3-triazol-4-yl)methyl)acetamide	1.349	0.0027	0.0264	0.0105	0.0710
Hydrochloric acid	0.463	0.0009	0.4630 ^b		

H ₂ O	0.983	0.0020		0.9810	
Dichloromethane	1.659	0.0033	0.4065	0.1609	1.0916
Methanol	3.956	0.0079	0.9692	0.3837	2.6030
Acetic acid ^a			0.0821	0.0325	0.2204
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aReaction side product; ^bEmitted as gaseous hydrochloric acid

Table SI-19. Synthesis of copper (I) bromide (Adapted from ref. 24)

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Copper sulfate	2.393			0.0837	0.0837
Sodium bromide ^a	2.185			0.3753	0.3753
Sodium sulfite	0.945			0.0331	0.0331
H ₂ O	22.490	0.0450		22.3101	
Sodium sulfate ^b			0.5216	1.0645	1.0645
Sulfuric acid ^b			0.1801	0.3675	0.3675
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

^aSodium chloride used instead of sodium bromide; ^bReaction side product

Table SI-20. Synthesis of triphenylphosphine (PPh₃)²⁵

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Sodium	0.558			0.2351	0.2351
Chlorobenzene	1.382	0.0028	0.0232	0.0092	0.0623
Phosphorous chloride	0.544			0.0103	0.0136
Toluene	5.260	0.0105	1.2888	0.5102	3.4613
Sodium chloride ^a				0.5790	0.5790
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				

Chemical factory	4xE-13 p				
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^aReaction side product

Table SI-21. Synthesis of tris(triphenylphosphine)copper(I) bromide [CuBr(PPh₃)₃]²⁶

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Copper (I) bromide	0.169			0.0076	0.0076
Triphenylphosphine	0.929		0.2277	0.0902	0.6116
Acetonitrile	19.712	0.0394	4.8294	1.9121	12.9705
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

Table SI-22. Synthesis of Polarclean® (Adapted from ref. 27)

Materials flow	Quantity (g) for 1 g of product	Process air emissions (g)	Wastewater treatment emissions (g)		
			CO ₂ to air	Compounds to river	Final waste flow (sludge)
Butadiene	0.055				
Hydrogen cyanide	0.055				
Sodium hydroxyde	0.040				
Sulfuric acid	0.100				
H ₂ O	0.037				
Acetic anhydride	0.229				
Methanol	0.652				
Thionyl chloride	0.242				
Dimethylacetamide	0.177				
Triethylamine	0.128				
Toluene	0.094				
Electricity	0.000333 KWh				
Steam	0.0002 MJ				
Transport (lorry 16-32 t)	1.00xE-4 tkm				
Transport (train)	6.00xE-4 tkm				
Chemical factory	4xE-13 p				

Table SI-23 List of the activities used for the inventories construction, retrieved from Ecoinvent database (version 3.11)

Source	Comments
Acetic acid {GLO} market for acetic acid Cut-off, S	
Acetic anhydride {GLO} market for acetic anhydride Cut-off, S	

Activated silica {GLO} market for activated silica Cut-off, S	
Acetonitrile {GLO} market for acetonitrile Cut-off, S	
Ammonia, anhydrous, liquid {RER} market for ammonia, anhydrous, liquid Cut-off, S	
Ammonium chloride {GLO} market for ammonium chloride Cut-off, S	
Ascorbic acid {GLO} market for ascorbic acid Cut-off, S	
Benzyl chloride {RER} market for benzyl chloride Cut-off, S	
Bromine {GLO} market for bromine Cut-off,	
Butadiene {RER} market for butadiene Cut-off, S	
Chemical factory, organics {GLO} market for chemical factory, organics Cut-off, S	
Copper, cathode {GLO} market for copper, cathode Cut-off, S	
Copper sulfate {GLO} market for copper sulfate Cut-off, S	
Dichloromethane {RER} market for dichloromethane Cut-off, S	
Diethyl ether, without water, in 99.95% solution state {RER} market for diethyl ether, without water, in 99.95% solution state Cut-off, S	
Dimethylacetamide {GLO} market for dimethylacetamide Cut-off, S	
Dimethyl sulfoxide {GLO} market for dimethyl sulfoxide Cut-off, S	
Electricity, low voltage {RER} market group for electricity, low voltage Cut-off, S	
Ethanol, without water, in 99.7% solution state, from ethylene {RER} market for ethanol, without water, in 99.7% solution state, from ethylene Cut-off, S	
Epichlorohydrin {GLO} market for epichlorohydrin Cut-off, S	
Ethyl acetate {GLO} market for ethyl acetate Cut-off, S	For the Lal et al. procedure, its amount as purification solvent was assumed
Heat, from steam, in chemical industry {RER} market for heat, from steam, in chemical industry Cut-off, S	
Hexane {GLO} market for hexane Cut-off, S	
Hydrochloric acid, without water, in 30% solution state {RER} market for hydrochloric acid, without water, in 30% solution state Cut-off, S	
Hydrogen cyanide {RER} market for hydrogen cyanide Cut-off, S	
Hydrazine {RER} market for hydrazine Cut-off, S	For the synthesis of sodium azide, was used as a proxy for hydrazine hydrate
Iron pellet {GLO} market for iron pellet Cut-off, S	
Isobutanol {RER} market for isobutanol Cut-off, S	For the Chan et al., Rostovtsev et al. and Himo et al.

	procedure, was used as a proxy for tBuOH
Isopropanol {RER} market for isopropanol Cut-off, S	
Magnesium sulfate {GLO} market for magnesium sulfate Cut-off, S	
Methanol {RER} market for methanol Cut-off, S	
Monochlorobenzene {RER} market for monochlorobenzene Cut-off, S	
Nitric acid, without water, in 50% solution state {RER w/o RU} market for nitric acid, without water, in 50% solution state Cut-off, S	
Phosphorous chloride {RER} market for phosphorous chloride Cut-off, S	For the synthesis of -bromoprop-1-yne, was used as a proxy for phosphorous tribromide
Potassium carbonate {GLO} market for potassium carbonate Cut-off, S	
Potassium hydroxide {GLO} market for potassium hydroxide Cut-off, S	
Sodium {GLO} market for sodium Cut-off, S	
Sodium amide {RER} market for sodium amide Cut-off, S	
Sodium bicarbonate {RER} market for sodium bicarbonate Cut-off, S	
Sodium chloride, powder {GLO} market for sodium chloride, powder Cut-off, S	For the synthesis of copper (I) bromide, was used as a proxy for sodium bromide
Sodium hydroxide, without water, in 50% solution state {RER} market for sodium hydroxide, without water, in 50% solution state Cut-off, S	
Sodium nitrite {RER} market for sodium nitrite Cut-off, S	
Sodium sulfite {RER} market for sodium sulfite Cut-off, S	
Succinic acid {GLO} market for succinic acid Cut-off, S	
Sulfuric acid {RER} market for sulfuric acid Cut-off, S	
Styrene {RER} market for styrene Cut-off, S	
Thionyl chloride {RER} market for thionyl chloride Cut-off, S	
Toluene, liquid {RER} market for toluene, liquid Cut-off, S	
Transport, freight, lorry 16-32 metric ton, EURO6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, S	
Transport, freight train {RER} market group for transport, freight train Cut-off, S	
Triethyl amine {GLO} market for triethyl amine Cut-off, S	For the synthesis of sodium azide, was used as a proxy for tributyl amine
Water, deionised {Europe without Switzerland} market for water, deionised Cut-off, S	

3. LCA impact assessment dataset

Table SI-24. Midpoint characterization (%) of the Chan et al. procedure (ReCiPe 2016)

Impact category	Total (%)	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	Ligand	tBuOH	H ₂ O	Chemical factory
<i>Global warming</i>	100	0.5088	64.0116	13.4661	0.2050	0.0096	14.5222	7.2623	0.0006	0.0138
<i>Stratospheric ozone depletion</i>	100	0.0000	78.2916	0.6016	0.0191	0.0020	20.7617	0.3227	0.0001	0.0011
<i>Ionizing radiation</i>	100	0.0000	40.5984	16.6123	0.3469	0.0350	13.7645	28.5900	0.0021	0.0507
<i>Ozone formation. Human health</i>	100	0.0000	68.6175	13.0413	0.1403	0.0259	13.5505	4.6093	0.0004	0.0148
<i>Fine particulate matter formation</i>	100	0.0000	53.2939	9.6282	0.1175	0.0841	33.3623	3.4869	0.0008	0.0262
<i>Ozone formation. Terrestrial ecosystems</i>	100	0.0000	68.6558	13.7226	0.1453	0.0228	12.7471	4.6930	0.0003	0.0131
<i>Terrestrial acidification</i>	100	0.0000	37.1339	6.1247	0.0836	0.0660	54.2715	2.3036	0.0006	0.0161
<i>Freshwater eutrophication</i>	100	0.0000	57.7573	14.2696	0.2497	0.0607	19.7140	7.9214	0.0006	0.0266
<i>Marine eutrophication</i>	100	0.0000	17.8443	31.6922	0.4518	0.0167	46.7066	3.2804	0.0004	0.0075
<i>Terrestrial ecotoxicity</i>	100	0.0000	58.7183	23.0164	0.2518	0.1473	10.8713	6.9076	0.0010	0.0863
<i>Freshwater ecotoxicity</i>	100	0.0000	32.1124	56.2608	0.0218	0.0864	11.1284	0.3853	0.0002	0.0047
<i>Marine ecotoxicity</i>	100	0.0000	61.4418	19.7390	0.2625	0.2170	10.9525	7.3001	0.0013	0.0856
<i>Human carcinogenic toxicity</i>	100	0.0000	68.7097	10.1446	0.1273	0.2214	16.6279	4.0715	0.0014	0.0961
<i>Human non-carcinogenic toxicity</i>	100	0.0000	74.0291	10.7022	0.1272	0.5438	10.7227	3.7813	0.0009	0.0929
<i>Land use</i>	100	0.0000	63.6297	16.4691	0.7521	0.0817	9.6006	9.3838	0.0008	0.0823
<i>Mineral resource scarcity</i>	100	0.0000	59.0382	23.0401	0.2089	0.4792	11.4807	5.5930	0.0012	0.1587
<i>Fossil resource scarcity</i>	100	0.0000	62.8897	17.3690	0.2116	0.0051	11.4337	8.0836	0.0003	0.0069
<i>Water consumption</i>	100	-0.1410	49.2777	12.2626	0.2108	0.0268	10.8582	27.3433	0.1465	0.0151

Table SI-25. Midpoint characterization (units) of the Chan et al. procedure (ReCiPe 2016)

Impact category	Unit	Total	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	Ligand	tBuOH	H ₂ O	Chemical factory
<i>Global warming</i>	kg CO ₂ eq	4.56E-01	2.32E-03	2.92E-01	6.14E-02	9.34E-04	4.37E-05	6.62E-02	3.31E-02	2.51E-06	6.30E-05
<i>Stratospheric ozone depletion</i>	kg CFC11 eq	2.06E-06	0.00E+00	1.62E-06	1.24E-08	3.94E-10	4.18E-11	4.29E-07	6.66E-09	1.88E-12	2.33E-11
<i>Ionizing radiation</i>	kBq Co-60 eq	9.12E-04	0.00E+00	3.70E-04	1.51E-04	3.16E-06	3.19E-07	1.26E-04	2.61E-04	1.93E-08	4.63E-07
<i>Ozone formation. Human health</i>	kg NO _x eq	1.32E-03	0.00E+00	9.05E-04	1.72E-04	1.85E-06	3.42E-07	1.79E-04	6.08E-05	4.71E-09	1.95E-07
<i>Fine particulate matter formation</i>	kg PM _{2.5} eq	7.77E-04	0.00E+00	4.14E-04	7.48E-05	9.13E-07	6.53E-07	2.59E-04	2.71E-05	6.58E-09	2.03E-07
<i>Ozone formation. Terrestrial ecosystems</i>	kg NO _x eq	1.54E-03	0.00E+00	1.05E-03	2.11E-04	2.23E-06	3.49E-07	1.96E-04	7.21E-05	4.92E-09	2.01E-07
<i>Terrestrial acidification</i>	kg SO ₂ eq	3.07E-03	0.00E+00	1.14E-03	1.88E-04	2.56E-06	2.02E-06	1.66E-03	7.06E-05	1.87E-08	4.95E-07
<i>Freshwater eutrophication</i>	kg P eq	1.98E-05	0.00E+00	1.14E-05	2.82E-06	4.94E-08	1.20E-08	3.90E-06	1.57E-06	1.23E-10	5.27E-09
<i>Marine eutrophication</i>	kg N eq	9.08E-06	0.00E+00	1.62E-06	2.88E-06	4.10E-08	1.51E-09	4.24E-06	2.98E-07	3.32E-11	6.81E-10
<i>Terrestrial ecotoxicity</i>	kg 1,4-DCB	3.26E+00	0.00E+00	1.91E+00	7.50E-01	8.21E-03	4.80E-03	3.54E-01	2.25E-01	3.40E-05	2.81E-03

<i>Freshwater ecotoxicity</i>	kg 1,4-DCB	4.96E-03	0.00E+00	1.59E-03	2.79E-03	1.08E-06	4.28E-06	5.52E-04	1.91E-05	9.98E-09	2.33E-07
<i>Marine ecotoxicity</i>	kg 1,4-DCB	3.59E-03	0.00E+00	2.21E-03	7.09E-04	9.43E-06	7.80E-06	3.93E-04	2.62E-04	4.82E-08	3.08E-06
<i>Human carcinogenic toxicity</i>	kg 1,4-DCB	2.44E-03	0.00E+00	1.68E-03	2.48E-04	3.11E-06	5.41E-06	4.06E-04	9.95E-05	3.43E-08	2.35E-06
<i>Human non-carcinogenic toxicity</i>	kg 1,4-DCB	1.27E-01	0.00E+00	9.41E-02	1.36E-02	1.62E-04	6.91E-04	1.36E-02	4.80E-03	1.21E-06	1.18E-04
<i>Land use</i>	m ² a crop eq	9.39E-03	0.00E+00	5.98E-03	1.55E-03	7.06E-05	7.67E-06	9.02E-04	8.81E-04	7.45E-08	7.73E-06
<i>Mineral resource scarcity</i>	kg Cu eq	1.66E-03	0.00E+00	9.77E-04	3.81E-04	3.46E-06	7.93E-06	1.90E-04	9.26E-05	1.93E-08	2.63E-06
<i>Fossil resource scarcity</i>	kg oil eq	2.16E-01	0.00E+00	1.36E-01	3.75E-02	4.56E-04	1.11E-05	2.47E-02	1.74E-02	6.26E-07	1.49E-05
<i>Water consumption</i>	m ³	4.21E-03	-5.94E-06	2.07E-03	5.16E-04	8.87E-06	1.13E-06	4.57E-04	1.15E-03	6.17E-06	6.37E-07

Table SI-26. Midpoint characterization (%) of the Rostovtsev et al. procedure (ReCiPe 2016)

Impact category	Total (%)	Synthetic procedure	Phenyl acetylene	Benzyl azide	tBuOH	H₂O	Cu (0)	Chemical factory
<i>Global warming</i>	100	0.4419	74.7919	15.7339	6.3798	0.0131	2.6232	0.0161
<i>Stratospheric ozone depletion</i>	100	0.0000	98.1932	0.7546	0.3043	0.0023	0.7442	0.0014
<i>Ionizing radiation</i>	100	0.0000	46.4985	19.0266	24.6195	0.0492	9.7481	0.0581
<i>Ozone formation. Human health</i>	100	0.0000	74.0948	14.0823	3.7422	0.0078	8.0570	0.0160
<i>Fine particulate matter formation</i>	100	0.0000	58.6503	10.5959	2.8852	0.0189	27.8209	0.0288
<i>Ozone formation. Terrestrial ecosystems</i>	100	0.0000	74.2450	14.8397	3.8157	0.0070	7.0784	0.0141
<i>Terrestrial acidification</i>	100	0.0000	57.1886	9.4324	2.6674	0.0191	30.6676	0.0249
<i>Freshwater eutrophication</i>	100	0.0000	59.7595	14.7642	6.1622	0.0131	19.2735	0.0275
<i>Marine eutrophication</i>	100	0.0000	31.2446	55.4916	4.3186	0.0130	8.9191	0.0131
<i>Terrestrial ecotoxicity</i>	100	0.0000	45.7994	17.9524	4.0509	0.0165	32.1135	0.0673
<i>Freshwater ecotoxicity</i>	100	0.0000	35.4778	62.1570	0.3200	0.0045	2.0354	0.0052
<i>Marine ecotoxicity</i>	100	0.0000	56.6725	18.2068	5.0626	0.0251	19.9540	0.0790
<i>Human carcinogenic toxicity</i>	100	0.0000	46.5293	6.8698	2.0730	0.0193	44.4435	0.0651
<i>Human non-carcinogenic toxicity</i>	100	0.0000	28.8019	4.1638	1.1061	0.0075	65.8846	0.0361
<i>Land use</i>	100	0.0000	57.0177	14.7577	6.3221	0.0144	21.8143	0.0737
<i>Mineral resource scarcity</i>	100	0.0000	25.1849	9.8286	1.7939	0.0101	63.1149	0.0677
<i>Fossil resource scarcity</i>	100	0.0000	71.8310	19.8385	6.9418	0.0067	1.3740	0.0079
<i>Water consumption</i>	100	-3.2118	55.2978	13.7607	23.0698	3.3377	7.7290	0.0170

Table SI-27. Midpoint characterization (units) of the Rostovtsev et al. procedure (ReCiPe 2016)

Impact category	Unit	Total	Synthetic procedure	Phenyl acetylene	Benzyl azide	tBuOH	H₂O	Cu (0)	Chemical factory
<i>Global warming</i>	kg CO ₂ eq	3.90E-01	1.72E-03	2.92E-01	6.14E-02	2.49E-02	5.10E-05	1.02E-02	6.30E-05
<i>Stratospheric ozone depletion</i>	kg CFC11 eq	1.65E-06	0.00E+00	1.62E-06	1.24E-08	5.01E-09	3.82E-11	1.23E-08	2.33E-11
<i>Ionizing radiation</i>	kBq Co-60 eq	7.96E-04	0.00E+00	3.70E-04	1.51E-04	1.96E-04	3.92E-07	7.76E-05	4.63E-07
<i>Ozone formation. Human health</i>	kg NOx eq	1.22E-03	0.00E+00	9.05E-04	1.72E-04	4.57E-05	9.57E-08	9.84E-05	1.95E-07
<i>Fine particulate matter formation</i>	kg PM2.5 eq	7.06E-04	0.00E+00	4.14E-04	7.48E-05	2.04E-05	1.34E-07	1.96E-04	2.03E-07
<i>Ozone formation. Terrestrial ecosystems</i>	kg NOx eq	1.42E-03	0.00E+00	1.05E-03	2.11E-04	5.42E-05	9.98E-08	1.00E-04	2.01E-07
<i>Terrestrial acidification</i>	kg SO ₂ eq	1.99E-03	0.00E+00	1.14E-03	1.88E-04	5.31E-05	3.80E-07	6.10E-04	4.95E-07
<i>Freshwater eutrophication</i>	kg P eq	1.91E-05	0.00E+00	1.14E-05	2.82E-06	1.18E-06	2.50E-09	3.69E-06	5.27E-09
<i>Marine eutrophication</i>	kg N eq	5.18E-06	0.00E+00	1.62E-06	2.88E-06	2.24E-07	6.74E-10	4.62E-07	6.81E-10

<i>Terrestrial ecotoxicity</i>	kg 1,4-DCB	4.18E+00	0.00E+00	1.91E+00	7.50E-01	1.69E-01	6.90E-04	1.34E+00	2.81E-03
<i>Freshwater ecotoxicity</i>	kg 1,4-DCB	4.49E-03	0.00E+00	1.59E-03	2.79E-03	1.44E-05	2.03E-07	9.14E-05	2.33E-07
<i>Marine ecotoxicity</i>	kg 1,4-DCB	3.89E-03	0.00E+00	2.21E-03	7.09E-04	1.97E-04	9.78E-07	7.77E-04	3.08E-06
<i>Human carcinogenic toxicity</i>	kg 1,4-DCB	3.61E-03	0.00E+00	1.68E-03	2.48E-04	7.48E-05	6.97E-07	1.60E-03	2.35E-06
<i>Human non-carcinogenic toxicity</i>	kg 1,4-DCB	3.27E-01	0.00E+00	9.41E-02	1.36E-02	3.61E-03	2.45E-05	2.15E-01	1.18E-04
<i>Land use</i>	m ² a crop eq	1.05E-02	0.00E+00	5.98E-03	1.55E-03	6.63E-04	1.51E-06	2.29E-03	7.73E-06
<i>Mineral resource scarcity</i>	kg Cu eq	3.88E-03	0.00E+00	9.77E-04	3.81E-04	6.96E-05	3.91E-07	2.45E-03	2.63E-06
<i>Fossil resource scarcity</i>	kg oil eq	1.89E-01	0.00E+00	1.36E-01	3.75E-02	1.31E-02	1.27E-05	2.59E-03	1.49E-05
<i>Water consumption</i>	m ³	3.75E-03	-1.20E-04	2.07E-03	5.16E-04	8.65E-04	1.25E-04	2.90E-04	6.37E-07

Table SI-28. Midpoint characterization (%) of the Himo et al. procedure (ReCiPe 2016)

Impact category	Total (%)	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	tBuOH	H ₂ O	Chemical factory
<i>Global warming</i>	100	0.4567	76.3182	16.0550	0.6146	0.0114	6.5100	0.0175	0.0165
<i>Stratospheric ozone depletion</i>	100	0.0000	98.8662	0.7597	0.0606	0.0026	0.3064	0.0031	0.0014
<i>Ionizing radiation</i>	100	0.0000	50.9257	20.8382	1.0942	0.0438	26.9636	0.0708	0.0636
<i>Ozone formation. Human health</i>	100	0.0000	80.2287	15.2481	0.4124	0.0303	4.0520	0.0111	0.0173
<i>Fine particulate matter formation</i>	100	0.0000	80.7825	14.5943	0.4479	0.1275	3.9739	0.0342	0.0397
<i>Ozone formation. Terrestrial ecosystems</i>	100	0.0000	79.5395	15.8980	0.4232	0.0264	4.0879	0.0099	0.0152
<i>Terrestrial acidification</i>	100	0.0000	81.9749	13.5205	0.4639	0.1457	3.8235	0.0359	0.0356
<i>Freshwater eutrophication</i>	100	0.0000	73.3758	18.1283	0.7976	0.0772	7.5662	0.0211	0.0338
<i>Marine eutrophication</i>	100	0.0000	33.5590	59.6022	2.1365	0.0313	4.6385	0.0183	0.0141
<i>Terrestrial ecotoxicity</i>	100	0.0000	66.8600	26.2077	0.7209	0.1678	5.9136	0.0317	0.0982
<i>Freshwater ecotoxicity</i>	100	0.0000	36.1568	63.3465	0.0619	0.0973	0.3262	0.0060	0.0053
<i>Marine ecotoxicity</i>	100	0.0000	70.0847	22.5157	0.7528	0.2476	6.2607	0.0408	0.0977
<i>Human carcinogenic toxicity</i>	100	0.0000	83.1931	12.2830	0.3876	0.2681	3.7065	0.0454	0.1164
<i>Human non-carcinogenic toxicity</i>	100	0.0000	83.5959	12.0852	0.3610	0.6140	3.2104	0.0286	0.1049
<i>Land use</i>	100	0.0000	71.3096	18.4568	2.1193	0.0915	7.9068	0.0237	0.0922
<i>Mineral resource scarcity</i>	100	0.0000	67.4895	26.3383	0.6003	0.5478	4.8071	0.0355	0.1814
<i>Fossil resource scarcity</i>	100	0.0000	72.3800	19.9901	0.6123	0.0059	6.9949	0.0089	0.0079
<i>Water consumption</i>	100	-4.5382	59.5014	14.8067	0.6400	0.0323	24.8235	4.7160	0.0183

Table SI-29. Midpoint characterization (units) of the Himo et al. procedure (ReCiPe 2016)

Impact category	Unit	Total	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	tBuOH	H ₂ O	Chemical factory
<i>Global warming</i>	kg CO ₂ eq	3.82E-01	1.75E-03	2.92E-01	6.14E-02	2.35E-03	4.37E-05	2.49E-02	6.70E-05	6.30E-05
<i>Stratospheric ozone depletion</i>	kg CFC11 eq	1.63E-06	0.00E+00	1.62E-06	1.24E-08	9.91E-10	4.18E-11	5.01E-09	5.01E-11	2.33E-11
<i>Ionizing radiation</i>	kBq Co-60 eq	7.27E-04	0.00E+00	3.70E-04	1.51E-04	7.96E-06	3.19E-07	1.96E-04	5.15E-07	4.63E-07
<i>Ozone formation. Human health</i>	kg NOx eq	1.13E-03	0.00E+00	9.05E-04	1.72E-04	4.65E-06	3.42E-07	4.57E-05	1.26E-07	1.95E-07
<i>Fine particulate matter formation</i>	kg PM2.5 eq	5.13E-04	0.00E+00	4.14E-04	7.48E-05	2.30E-06	6.53E-07	2.04E-05	1.76E-07	2.03E-07
<i>Ozone formation. Terrestrial ecosystems</i>	kg NOx eq	1.33E-03	0.00E+00	1.05E-03	2.11E-04	5.61E-06	3.49E-07	5.42E-05	1.31E-07	2.01E-07

<i>Terrestrial acidification</i>	kg SO ₂ eq	1.39E-03	0.00E+00	1.14E-03	1.88E-04	6.44E-06	2.02E-06	5.31E-05	4.98E-07	4.95E-07
<i>Freshwater eutrophication</i>	kg P eq	1.56E-05	0.00E+00	1.14E-05	2.82E-06	1.24E-07	1.20E-08	1.18E-06	3.28E-09	5.27E-09
<i>Marine eutrophication</i>	kg N eq	4.83E-06	0.00E+00	1.62E-06	2.88E-06	1.03E-07	1.51E-09	2.24E-07	8.85E-10	6.81E-10
<i>Terrestrial ecotoxicity</i>	kg 1,4-DCB	2.86E+00	0.00E+00	1.91E+00	7.50E-01	2.06E-02	4.80E-03	1.69E-01	9.06E-04	2.81E-03
<i>Freshwater ecotoxicity</i>	kg 1,4-DCB	4.40E-03	0.00E+00	1.59E-03	2.79E-03	2.72E-06	4.28E-06	1.44E-05	2.66E-07	2.33E-07
<i>Marine ecotoxicity</i>	kg 1,4-DCB	3.15E-03	0.00E+00	2.21E-03	7.09E-04	2.37E-05	7.80E-06	1.97E-04	1.28E-06	3.08E-06
<i>Human carcinogenic toxicity</i>	kg 1,4-DCB	2.02E-03	0.00E+00	1.68E-03	2.48E-04	7.82E-06	5.41E-06	7.48E-05	9.15E-07	2.35E-06
<i>Human non-carcinogenic toxicity</i>	kg 1,4-DCB	1.13E-01	0.00E+00	9.41E-02	1.36E-02	4.06E-04	6.91E-04	3.61E-03	3.21E-05	1.18E-04
<i>Land use</i>	m ² a crop eq	8.38E-03	0.00E+00	5.98E-03	1.55E-03	1.78E-04	7.67E-06	6.63E-04	1.98E-06	7.73E-06
<i>Mineral resource scarcity</i>	kg Cu eq	1.45E-03	0.00E+00	9.77E-04	3.81E-04	8.69E-06	7.93E-06	6.96E-05	5.14E-07	2.63E-06
<i>Fossil resource scarcity</i>	kg oil eq	1.87E-01	0.00E+00	1.36E-01	3.75E-02	1.15E-03	1.11E-05	1.31E-02	1.67E-05	1.49E-05
<i>Water consumption</i>	m ³	3.49E-03	-1.58E-04	2.07E-03	5.16E-04	2.23E-05	1.13E-06	8.65E-04	1.64E-04	6.37E-07

Table SI-30. Midpoint characterization (%) of the Lal et al. procedure (ReCiPe 2016)

Impact category	Total (%)	Synthetic procedure	Phenyl acetylene	Benzyl azide	CuBr(PPh ₃) ₃	Ethyl acetate	Chemical factory
<i>Global warming</i>	100	0.9211	67.9685	14.2985	0.7564	16.0407	0.0147
<i>Stratospheric ozone depletion</i>	100	0.0000	98.2908	0.7553	0.0297	0.9228	0.0014
<i>Ionizing radiation</i>	100	0.0000	49.5877	20.2906	0.9384	29.1213	0.0620
<i>Ozone formation. Human health</i>	100	0.1777	72.9117	13.8574	0.4333	12.6042	0.0157
<i>Fine particulate matter formation</i>	100	0.0000	71.0328	12.8329	0.6430	15.4563	0.0349
<i>Ozone formation. Terrestrial ecosystems</i>	100	0.2454	72.8217	14.5552	0.4146	11.9492	0.0139
<i>Terrestrial acidification</i>	100	0.0000	73.8478	12.1801	0.7569	13.1831	0.0321
<i>Freshwater eutrophication</i>	100	0.0000	52.5766	12.9896	1.4496	32.9599	0.0242
<i>Marine eutrophication</i>	100	0.0000	24.3920	43.3212	26.6033	5.6731	0.0103
<i>Terrestrial ecotoxicity</i>	100	0.0203	59.8876	23.4747	1.4429	15.0865	0.0880
<i>Freshwater ecotoxicity</i>	100	0.5679	35.2940	61.8349	0.2483	2.0497	0.0052
<i>Marine ecotoxicity</i>	100	0.1192	62.5577	20.0975	1.4065	15.7319	0.0872
<i>Human carcinogenic toxicity</i>	100	0.0000	77.6843	11.4696	0.6805	10.0569	0.1087
<i>Human non-carcinogenic toxicity</i>	100	0.0202	74.3714	10.7517	0.7229	14.0406	0.0933
<i>Land use</i>	100	0.0000	63.6354	16.4705	0.7145	19.0973	0.0823
<i>Mineral resource scarcity</i>	100	0.0000	62.1397	24.2505	0.9959	12.4468	0.1670
<i>Fossil resource scarcity</i>	100	0.0000	66.4469	18.3515	0.6644	14.5300	0.0073
<i>Water consumption</i>	100	0.0000	62.6360	15.5868	0.9663	20.7917	0.0192

Table SI-31. Midpoint characterization (units) of the Lal et al. procedure (ReCiPe 2016)

Impact category	Unit	Total	Synthetic procedure	Phenyl acetylene	Benzyl azide	CuBr(PPh ₃) ₃	Ethyl acetate	Chemical factory
<i>Global warming</i>	kg CO ₂ eq	4.29E-01	3.95E-03	2.92E-01	6.14E-02	3.25E-03	6.89E-02	6.30E-05
<i>Stratospheric ozone depletion</i>	kg CFC11 eq	1.64E-06	0.00E+00	1.62E-06	1.24E-08	4.88E-10	1.52E-08	2.33E-11
<i>Ionizing radiation</i>	kBq Co-60 eq	7.47E-04	0.00E+00	3.70E-04	1.51E-04	7.01E-06	2.17E-04	4.63E-07
<i>Ozone formation. Human health</i>	kg NOx eq	1.24E-03	2.20E-06	9.05E-04	1.72E-04	5.38E-06	1.56E-04	1.95E-07
<i>Fine particulate matter formation</i>	kg PM2.5 eq	5.83E-04	0.00E+00	4.14E-04	7.48E-05	3.75E-06	9.01E-05	2.03E-07
<i>Ozone formation. Terrestrial ecosystems</i>	kg NOx eq	1.45E-03	3.55E-06	1.05E-03	2.11E-04	6.00E-06	1.73E-04	2.01E-07
<i>Terrestrial acidification</i>	kg SO ₂ eq	1.54E-03	0.00E+00	1.14E-03	1.88E-04	1.17E-05	2.03E-04	4.95E-07
<i>Freshwater eutrophication</i>	kg P eq	2.17E-05	0.00E+00	1.14E-05	2.82E-06	3.15E-07	7.16E-06	5.27E-09

<i>Marine eutrophication</i>	kg N eq	6.64E-06	0.00E+00	1.62E-06	2.88E-06	1.77E-06	3.77E-07	6.81E-10
<i>Terrestrial ecotoxicity</i>	kg 1,4-DCB	3.19E+00	6.49E-04	1.91E+00	7.50E-01	4.61E-02	4.82E-01	2.81E-03
<i>Freshwater ecotoxicity</i>	kg 1,4-DCB	4.51E-03	2.56E-05	1.59E-03	2.79E-03	1.12E-05	9.25E-05	2.33E-07
<i>Marine ecotoxicity</i>	kg 1,4-DCB	3.53E-03	4.21E-06	2.21E-03	7.09E-04	4.96E-05	5.55E-04	3.08E-06
<i>Human carcinogenic toxicity</i>	kg 1,4-DCB	2.16E-03	0.00E+00	1.68E-03	2.48E-04	1.47E-05	2.17E-04	2.35E-06
<i>Human non-carcinogenic toxicity</i>	kg 1,4-DCB	1.26E-01	2.55E-05	9.41E-02	1.36E-02	9.14E-04	1.78E-02	1.18E-04
<i>Land use</i>	m ² a crop eq	9.39E-03	0.00E+00	5.98E-03	1.55E-03	6.71E-05	1.79E-03	7.73E-06
<i>Mineral resource scarcity</i>	kg Cu eq	1.57E-03	0.00E+00	9.77E-04	3.81E-04	1.57E-05	1.96E-04	2.63E-06
<i>Fossil resource scarcity</i>	kg oil eq	2.04E-01	0.00E+00	1.36E-01	3.75E-02	1.36E-03	2.97E-02	1.49E-05
<i>Water consumption</i>	m ³	3.31E-03	0.00E+00	2.07E-03	5.16E-04	3.20E-05	6.89E-04	6.37E-07

Table SI-32. Midpoint characterization (%) of the Luciani et al. procedure (ReCiPe 2016)

Impact category	Total (%)	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	Poalrclean®	H₂O	Chemical factory
<i>Global warming</i>	100	0.1079	80.4914	16.9329	0.6630	0.0048	1.7821	0.0006	0.0174
<i>Stratospheric ozone depletion</i>	100	0.0000	99.0998	0.7615	0.0622	0.0010	0.0740	0.0001	0.0014
<i>Ionizing radiation</i>	100	0.0000	66.6234	27.2614	1.4640	0.0229	4.5422	0.0028	0.0832
<i>Ozone formation. Human health</i>	100	0.0000	82.7074	15.7192	0.4348	0.0125	1.1079	0.0004	0.0179
<i>Fine particulate matter formation</i>	100	0.0000	82.7460	14.9491	0.4692	0.0522	1.7418	0.0011	0.0406
<i>Ozone formation. Terrestrial ecosystems</i>	100	0.0000	82.0648	16.4027	0.4466	0.0109	1.0591	0.0003	0.0156
<i>Terrestrial acidification</i>	100	0.0000	83.8171	13.8244	0.4851	0.0596	1.7763	0.0011	0.0364
<i>Freshwater eutrophication</i>	100	0.0000	77.3394	19.1075	0.8598	0.0325	2.6244	0.0007	0.0356
<i>Marine eutrophication</i>	100	0.0000	32.5795	57.8624	2.1213	0.0122	7.4104	0.0005	0.0137
<i>Terrestrial ecotoxicity</i>	100	0.0000	70.6691	27.7008	0.7793	0.0709	0.6750	0.0010	0.1038
<i>Freshwater ecotoxicity</i>	100	0.0000	36.1125	63.2688	0.0632	0.0389	0.5112	0.0002	0.0053
<i>Marine ecotoxicity</i>	100	0.0000	74.0317	23.7837	0.8133	0.1046	1.1622	0.0013	0.1032
<i>Human carcinogenic toxicity</i>	100	0.0000	85.5022	12.6239	0.4074	0.1102	1.2353	0.0014	0.1196
<i>Human non-carcinogenic toxicity</i>	100	0.0000	85.8746	12.4146	0.3793	0.2523	0.9706	0.0009	0.1078
<i>Land use</i>	100	0.0000	76.2087	19.7249	2.3164	0.0391	1.6116	0.0008	0.0986
<i>Mineral resource scarcity</i>	100	0.0000	70.0958	27.3554	0.6377	0.2276	1.4940	0.0011	0.1884
<i>Fossil resource scarcity</i>	100	0.0000	76.4393	21.1112	0.6613	0.0025	1.7770	0.0003	0.0084
<i>Water consumption</i>	100	-0.1808	77.7824	19.3559	0.8557	0.0169	1.9582	0.1879	0.0239

Table SI-33. Midpoint characterization (units) of the Luciani et al. procedure (ReCiPe 2016)

Impact category	Unit	Total	Synthetic procedure	Phenyl acetylene	Benzyl azide	Sodium ascorbate	Copper sulfate	Poalrclean®	H₂O	Chemical factory
<i>Global warming</i>	kg CO ₂ eq	3.62E-01	3.91E-04	2.92E-01	6.14E-02	2.40E-03	1.75E-05	6.46E-03	2.04E-06	6.30E-05
<i>Stratospheric ozone depletion</i>	kg CFC11 eq	1.63E-06	0.00E+00	1.62E-06	1.24E-08	1.01E-09	1.67E-11	1.21E-09	1.53E-12	2.33E-11

<i>Ionizing radiation</i>	kBq Co-60 eq	5.56E-04	0.00E+00	3.70E-04	1.51E-04	8.14E-06	1.28E-07	2.52E-05	1.57E-08	4.63E-07
<i>Ozone formation. Human health</i>	kg NOx eq	1.09E-03	0.00E+00	9.05E-04	1.72E-04	4.76E-06	1.37E-07	1.21E-05	3.83E-09	1.95E-07
<i>Fine particulate matter formation</i>	kg PM2.5 eq	5.00E-04	0.00E+00	4.14E-04	7.48E-05	2.35E-06	2.61E-07	8.72E-06	5.35E-09	2.03E-07
<i>Ozone formation. Terrestrial ecosystems</i>	kg NOx eq	1.28E-03	0.00E+00	1.05E-03	2.11E-04	5.74E-06	1.40E-07	1.36E-05	4.00E-09	2.01E-07
<i>Terrestrial acidification</i>	kg SO ₂ eq	1.36E-03	0.00E+00	1.14E-03	1.88E-04	6.59E-06	8.09E-07	2.41E-05	1.52E-08	4.95E-07
<i>Freshwater eutrophication</i>	kg P eq	1.48E-05	0.00E+00	1.14E-05	2.82E-06	1.27E-07	4.81E-09	3.88E-07	1.00E-10	5.27E-09
<i>Marine eutrophication</i>	kg N eq	4.97E-06	0.00E+00	1.62E-06	2.88E-06	1.05E-07	6.05E-10	3.68E-07	2.70E-11	6.81E-10
<i>Terrestrial ecotoxicity</i>	kg 1,4-DCB	2.71E+00	0.00E+00	1.91E+00	7.50E-01	2.11E-02	1.92E-03	1.83E-02	2.76E-05	2.81E-03
<i>Freshwater ecotoxicity</i>	kg 1,4-DCB	4.41E-03	0.00E+00	1.59E-03	2.79E-03	2.79E-06	1.71E-06	2.25E-05	8.11E-09	2.33E-07
<i>Marine ecotoxicity</i>	kg 1,4-DCB	2.98E-03	0.00E+00	2.21E-03	7.09E-04	2.42E-05	3.12E-06	3.47E-05	3.92E-08	3.08E-06
<i>Human carcinogenic toxicity</i>	kg 1,4-DCB	1.96E-03	0.00E+00	1.68E-03	2.48E-04	8.00E-06	2.16E-06	2.43E-05	2.79E-08	2.35E-06
<i>Human non-carcinogenic toxicity</i>	kg 1,4-DCB	1.10E-01	0.00E+00	9.41E-02	1.36E-02	4.15E-04	2.76E-04	1.06E-03	9.80E-07	1.18E-04
<i>Land use</i>	m ² a crop eq	7.84E-03	0.00E+00	5.98E-03	1.55E-03	1.82E-04	3.07E-06	1.26E-04	6.05E-08	7.73E-06
<i>Mineral resource scarcity</i>	kg Cu eq	1.39E-03	0.00E+00	9.77E-04	3.81E-04	8.89E-06	3.17E-06	2.08E-05	1.57E-08	2.63E-06
<i>Fossil resource scarcity</i>	kg oil eq	1.77E-01	0.00E+00	1.36E-01	3.75E-02	1.17E-03	4.44E-06	3.15E-03	5.08E-07	1.49E-05
<i>Water consumption</i>	m ³	2.67E-03	-4.82E-06	2.07E-03	5.16E-04	2.28E-05	4.51E-07	5.22E-05	5.01E-06	6.37E-07

Table SI-34. Endpoint-single score comparison for the three damage areas considered among the procedures analyzed (ReCiPe 2016)

Damage area	Unit	Chan et al.	Rostovtsev et al.	Himo et al.	Lal et al.	Luciani et al.
Human health	mPts	15.9984	15.0330	11.9772	13.4971	11.5001
Ecosystems	mPts	0.6258	0.5139	0.4597	0.5122	0.4368
Resources	mPts	0.6091	0.5396	0.5343	0.5682	0.5065
Total	mPts	17.2333	16.0864	12.9711	14.5775	12.4434

Table SI-35. Endpoint unit values of the procedures considered (ReCiPe 2016)

Procedure	DALY	Species.yr	USD2013
Chan et al.	9.59E-7	2.31E-9	0.0853
Rostovtsev et al.	9.0E-7	1.9E-9	0.0756
Himo et al.	7.18E-7	1.7E-9	0.0748
Lal et al.	8.09E-7	1.89E-9	0.0796
Luciani et al.	6.89E-7	1.62E-9	0.0709

Table SI-36. Influence of the impact categories in the Endpoint-single score comparison among the procedures analyzed (ReCiPe 2016)

Impact category	Unit	Chan et al.	Rostovtsev et al.	Himo et al.	Lal et al.	Luciani et al.
<i>Global warming, Human health</i>	mPts	7.0558	6.0388	5.9180	6.6449	5.6112
<i>Global warming, Terrestrial ecosystems</i>	mPts	0.3453	0.2955	0.2896	0.3252	0.2746
<i>Global warming, Freshwater ecosystems</i>	mPts	9.43E-06	8.07E-06	7.91E-06	8.88E-06	7.50E-06
<i>Stratospheric ozone depletion</i>	mPts	0.0183	0.0146	0.0145	0.0146	0.0145
<i>Ionizing radiation</i>	mPts	0.0001	0.0001	0.0001	0.0001	0.0001
<i>Ozone formation, Human health</i>	mPts	0.0200	0.0185	0.0171	0.0188	0.0166
<i>Fine particulate matter formation</i>	mPts	8.1451	7.3974	5.3715	6.1090	5.2440
<i>Ozone formation, Terrestrial ecosystems</i>	mPts	0.0535	0.0495	0.0462	0.0505	0.0448
<i>Terrestrial acidification</i>	mPts	0.1758	0.1141	0.0796	0.0884	0.0779
<i>Freshwater eutrophication</i>	mPts	0.0036	0.0035	0.0028	0.0039	0.0027
<i>Marine eutrophication</i>	mPts	4.18E-06	2.39E-06	2.22E-06	3.06E-06	2.29E-06
<i>Terrestrial ecotoxicity</i>	mPts	0.0100	0.0129	0.0088	0.0099	0.0083
<i>Freshwater ecotoxicity</i>	mPts	0.0009	0.0008	0.0008	0.0008	0.0008
<i>Marine ecotoxicity</i>	mPts	0.0001	0.0001	0.0001	0.0001	0.0001
<i>Human carcinogenic toxicity</i>	mPts	0.1354	0.2000	0.1118	0.1198	0.1088
<i>Human non-carcinogenic toxicity</i>	mPts	0.4829	1.2408	0.4276	0.4806	0.4163
<i>Land use</i>	mPts	0.0225	0.0251	0.0201	0.0225	0.0188
<i>Mineral resource scarcity</i>	mPts	0.0027	0.0064	0.0024	0.0026	0.0023
<i>Fossil resource scarcity</i>	mPts	0.6063	0.5332	0.5319	0.5656	0.5042
<i>Water consumption, Human health</i>	mPts	0.1407	0.1227	0.1165	0.1093	0.0886
<i>Water consumption, Terrestrial ecosystem</i>	mPts	0.0140	0.0123	0.0116	0.0110	0.0089
<i>Water consumption, Aquatic ecosystems</i>	mPts	8.49E-07	7.78E-07	7.14E-07	7.50E-07	5.95E-07
Total	mPts	17.2333	16.0864	12.9711	14.5775	12.4434

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