Supporting Information for

Green Surfactants Powering Sustainable Batteries: Industrial-Scale Life Cycle Assessment of Tween and Span Surfactants for Battery Systems

Shiyu Wang [1], Likun Zhao [1], He Ye [1], Zhan Shi [2], Huakui Zhang [1], Fengyin Zhou [1], Simin Xu [1], Lei Xing [3], Dihua Wang [1, 4, 5 *], Huayi Yin [1, 4, 5 *]

1. School of Resource and Environmental Science, Wuhan University, 299 Bayi Road, Wuchang District, Wuhan 430072, P. R. China.
2. Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro (PD) 35020, Italy.
3. School of Chemistry and Chemical Engineering, University of Surrey, Guildford GU2 7XH, United Kingdom.
4. Hubei International Scientific and Technological Cooperation Base of Sustainable Resources and Energy, Wuhan 430072, P. R. China.
5. Hubei Provincial Key Laboratory of Biomass Resource Chemistry and Environmental Biotechnology, Wuhan 430072, P. R. China.

*Corresponding author. Email: yinhuayi@whu.edu.cn (Huayi Yin); wangdh@whu.edu.cn (Dihua Wang)

Number of supplementary pages:	48
Number of supplementary texts:	1
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Supplementary Texts:

Supplementary Figures:

Supplementary Tables:

Text S1. LCA of Tween 80-assisted synthesis for LIB anode.

Tween products are widely used in the energy sector, including the production of battery materials and electrolytes.[1-3] Here, Tween 80-assisted synthesis of silicon-carbon anodes for LIB was investigated as a case study.[4] Silicon anodes offer high theoretical capacity, but severe volume changes during charge-discharge cycles limit their commercial application.[5] Silicon-carbon composites can effectively mitigate silicon expansion.[6] However, particle aggregation occurs during silicon-carbon anode preparation.[7] Recent studies indicate Tween 80-assisted synthesis prevents aggregation and promotes more uniform distribution, leading to superior reversible capacity and electrode lifespan.[4] Notably, while these studies claim Tween 80 is environmentally friendly, they do not quantify the environmental impacts of Tween 80-assisted battery material synthesis. This gap likely arises from missing background environmental data for Tween 80. Therefore, an LCA was developed here to evaluate the environmental performance of Tween 80 use in battery material production.

Si/C-TW80 and Si/C denote silicon-carbon anodes produced with and without Tween 80, respectively. The functional unit was defined as the production of 1 kg of anode material. Based on prior research, the cycle life (the number of cycles until discharge capacity reached 70% of the initial capacity at 0.5 C, where 1 C = 130 mA/g for an LIB) was 53 cycles for Si/C-TW80 and 29 cycles for Si/C.[4] To reflect differences in service life within LIBs, environmental impacts and cumulative energy demand were also assessed using "one cycle" as the functional unit. The LCA system boundary encompassed direct emissions (waste gas, wastewater, and solid waste) and upstream processes (energy production and material manufacturing) involved in producing silicon-carbon anode material. Plant construction and equipment production/maintenance were excluded (Figure S7). Furthermore, as other battery components (cathode, separator, electrolyte, packaging) were identical, they were excluded from the boundary to focus the comparison on the anode.

The LCIs for Si/C-TW80 and Si/C are presented in Table S18. Inventory data were collected at the laboratory scale.[4] Production processes for Si/C-TW80 and Si/C differed slightly. First, thoroughly ball-milled silicon powder and graphite were mixed at a 1:1 mass ratio and ground. This mixture was added to an N, N-dimethylformamide (DMF) solution containing polyacrylonitrile (PAN). After constant stirring for 6 hours, it was mixed with a deionized water solution containing Tween 80 (Tween 80-to-water mass ratio of 1:200). Finally, the resulting solution was dried and calcined at 700 °C for 2 hours under an argon atmosphere to obtain Si/C-TW80. The PAN-to-DMF mass ratio was assumed to be 1:9. PAN was dissolved in DMF by stirring at 80 °C for 4 hours. Si/C was obtained by replacing the Tween 80 solution with deionized water, with other steps unchanged.

Grinding energy consumption ranged from 8 to 16 kWh/t; the upper limit of 16 kWh/t was adopted as the standard.[8] Production was assumed to occur in a 1,000 L vessel per batch (1,000 kg of material). Stirring and heating energy consumption (including temperature ramping and holding) was estimated using Eqs. S1 and S2.[8] All parameters used are consistent with the International System of Units (SI). `$E_{stirring}$`, `$\rho_{mix}$`, `$t$`, `$Q_{heat}$`, `$C_p$`, `$m_{mix}$`, and `$T$` represent stirring energy (J), mixture density (kg/m^3), stirring time (s), heating energy (J), specific heat capacity (J/kg·K), mixture mass (kg), and reaction temperature (K), respectively. Temperature-dependent variations in material-specific heat capacity were neglected.

The drying process was assumed to occur in a mechanical vapor recompression (MVR) evaporator. MVR evaporator energy consumption ranged from 20 to 50 kWh/t; the median value of 35 kWh/t was used as the representative value. Complete volatilization of water and DMF during drying was assumed, with a 95% recovery rate. PAN calcination products under inert gas were obtained from prior studies. Per kg PAN, calcination releases 0.121 kg HCN, 0.068 kg CO_2, 0.024 kg CO, 0.039 kg NH_3, and 0.014 kg CH_4.[9] Tween 80 was assumed fully decomposed during calcination. Per kg Tween 80, decomposition products were estimated as 0.4 kg CO_2, 0.15 kg CH_4, 0.2 kg non-methane volatile organic compounds, 0.1 kg solid residue, and 0.15 kg other substances (water, hydrogen, etc.). Greenhouse gas emissions from PAN under argon atmosphere were minimal and thus considered negligible. Argon consumption depended on initial purging cycles and system leakage. To ensure an inert atmosphere, vessel air was purged five times using nitrogen. A typical industrial vessel leakage rate ranges between 0.1 and 1 v%/h; the upper limit of 1 v%/h was adopted for this analysis. With a safety margin, the final argon consumption was set at 0.1 kg per kg of material.

The LCA method selection, uncertainty analysis, and sensitivity analysis aligned with the materials and methods section of this study. Environmental impact and energy demand assessment results for Si/C and Si/C-TW80 under different functional units are shown in Figures 7, S8, and S9. Uncertainty analysis results are presented in Figures S10 and S11 and Tables S19 and S20.

$$E_{stirring} = 0.018 * \rho_{mix} * t \quad \text{Eq. S1}$$

$$Q_{heat} = \frac{C_p * m_{mix} * (T - 298.15) + 3.303 * (T - 298.15) * t}{0.75} \quad \text{Eq. S2}$$

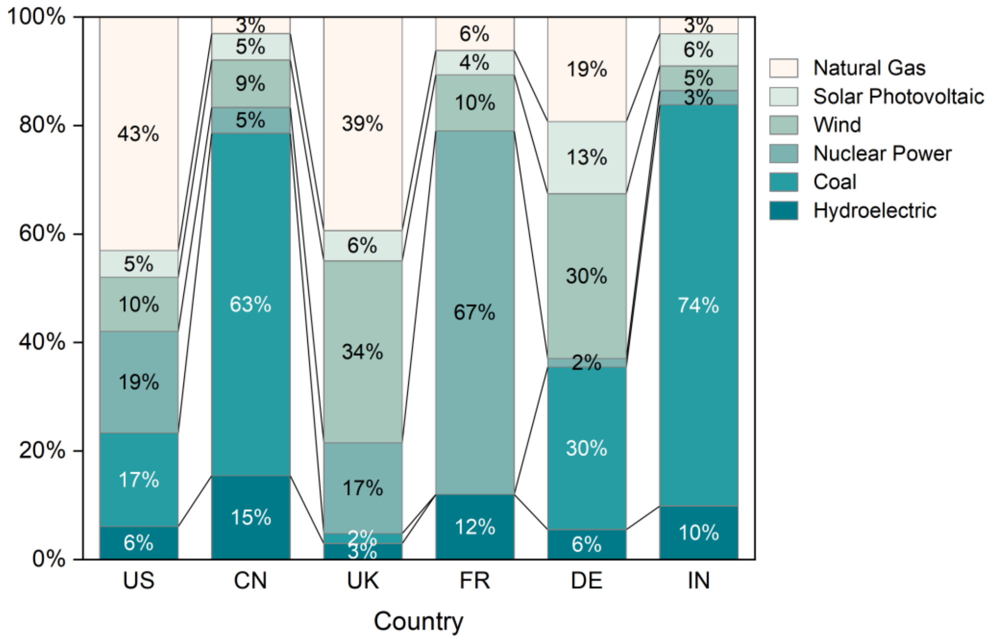

Figure S1. Electricity mixes of national grids across different countries.[10] Country codes: US (United States), CN (China), UK (United Kingdom), FR (France), DE (Germany), IN (India).

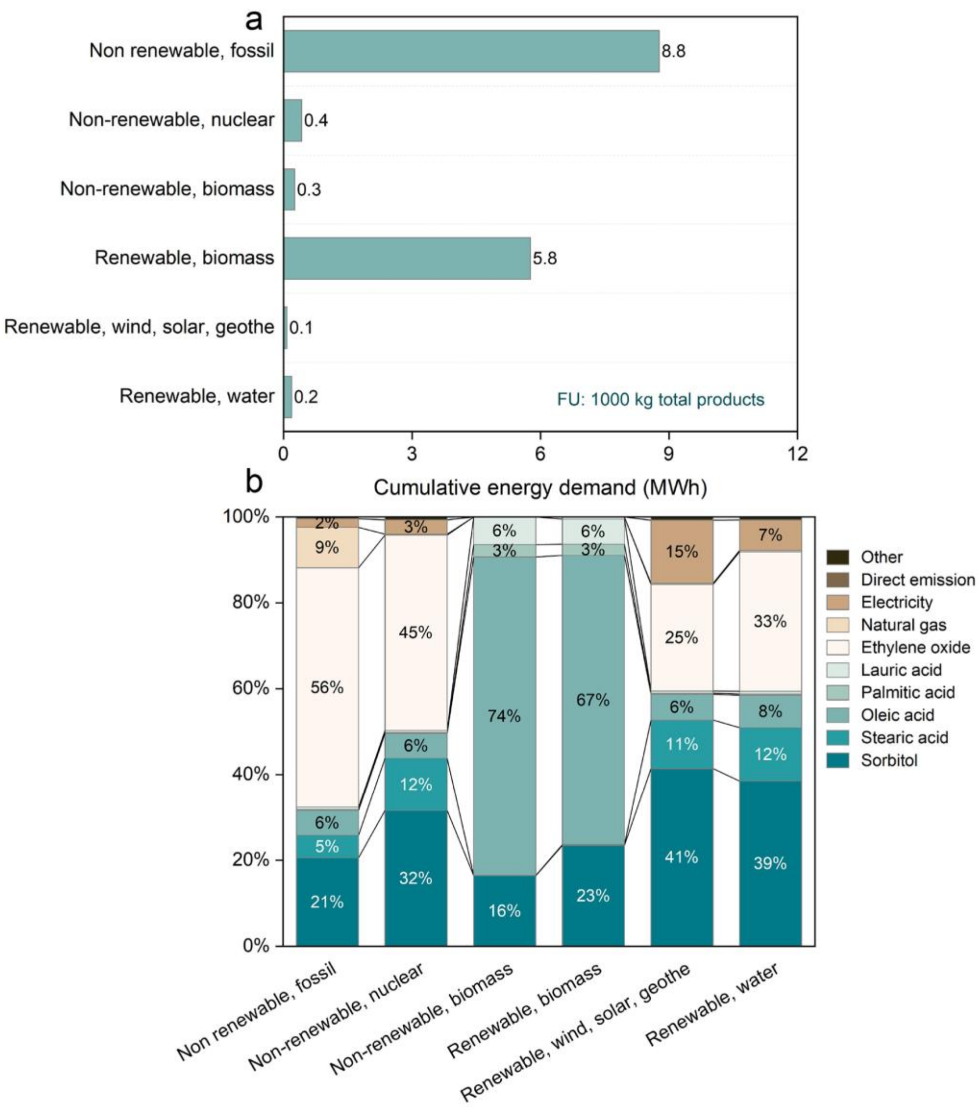

Figure S2. Contribution analysis of cumulative energy demand. (a) The distribution of different types of energy carriers. (b) The percentage distribution of material and energy inputs in different types of energy carriers.

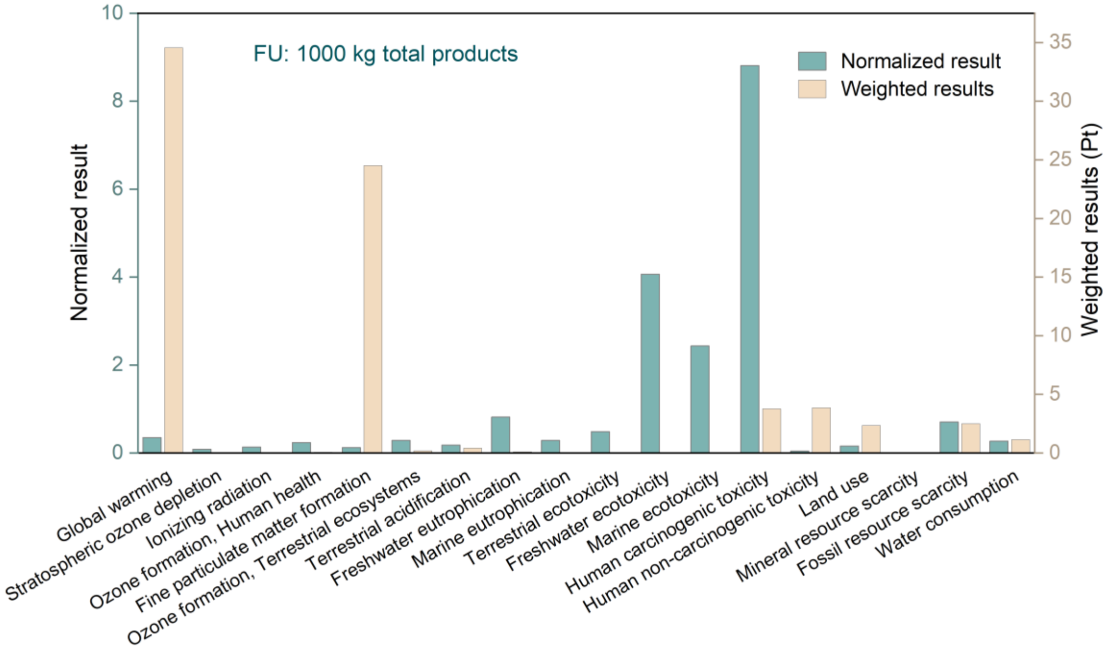

Figure S3. Normalized and weighted full-spectrum environmental impacts for the production of 1,000 kg of the total products.

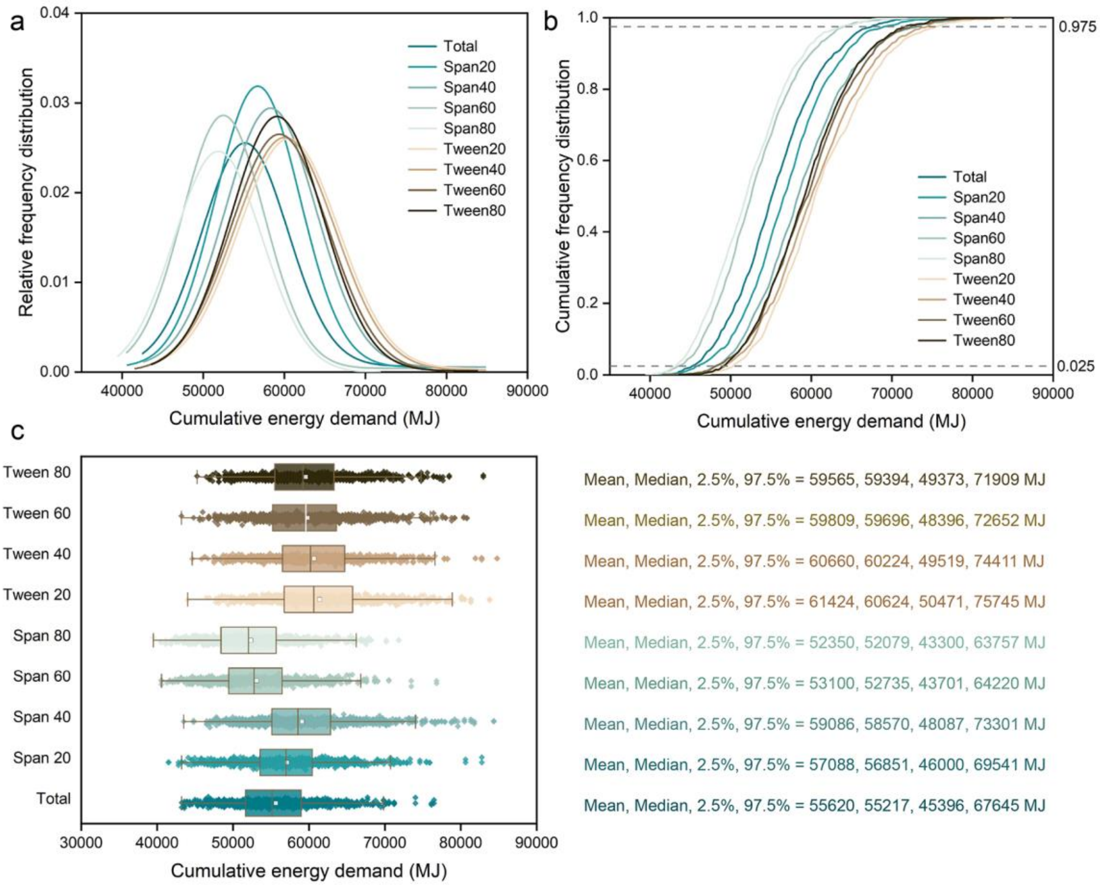

Figure S4. Uncertainty analysis of cumulative energy demand. (a) Relative frequency distribution, (b) cumulative frequency distribution, and (c) box plot distribution for the production of 1,000 kg of the total or specified products. Uncertainty distribution via 1,000 Monte-Carlo simulations. The dotted line indicates the 95% confidence interval. The rectangles within the box in the box plot represent the mean.

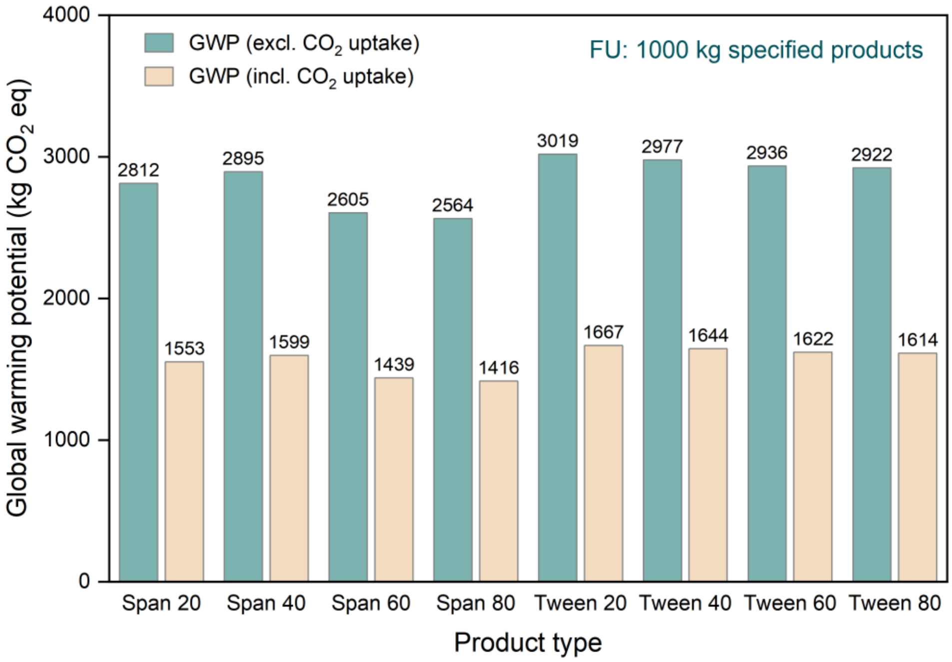

Figure S5. Global warming potential of including (incl.) and excluding (excl.) carbon uptake for the production of 1,000 kg of the specified products. GWP denote global warming potential.

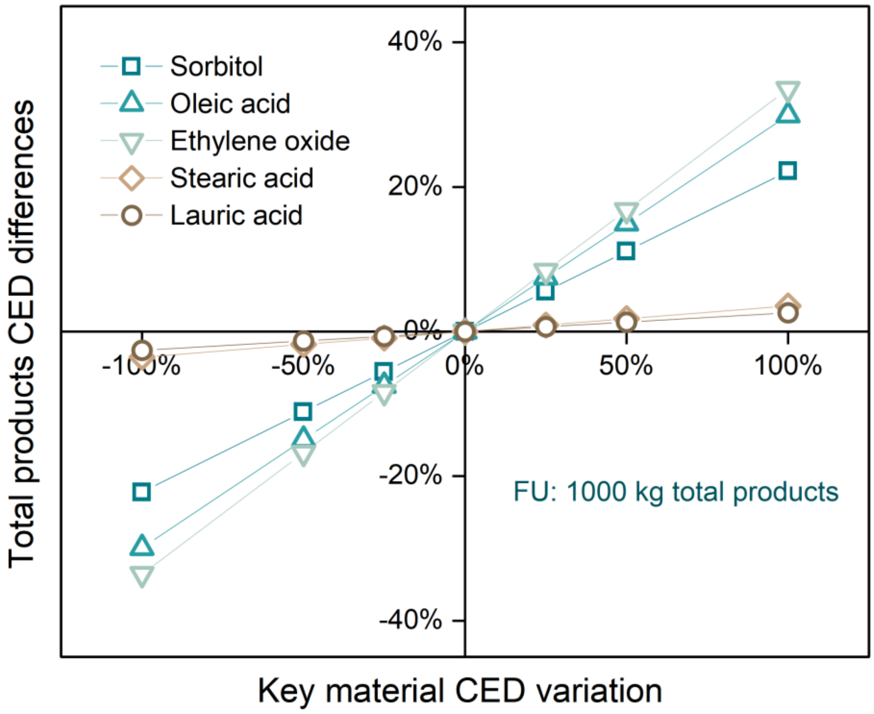

Figure S6. Impact of changes in the CED of key materials on the CED for the production of 1000 kg of the total products. CED denotes cumulative energy demand. Country codes: US (United States), CN (China), UK (United Kingdom), FR (France), DE (Germany), IN (India). Specifying key material CED changes of -100% and 100% mean that no CED and twice the CED are considered, respectively.

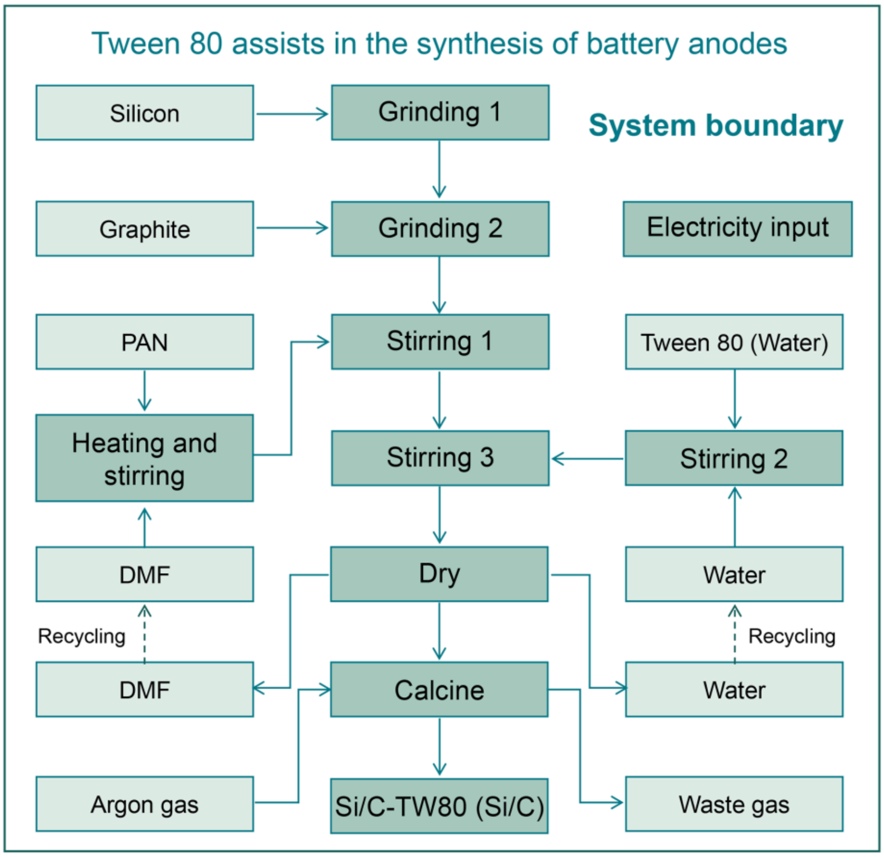

Figure S7. The system boundary for the synthesis of silicon-carbon anodes assisted by Tween 80.

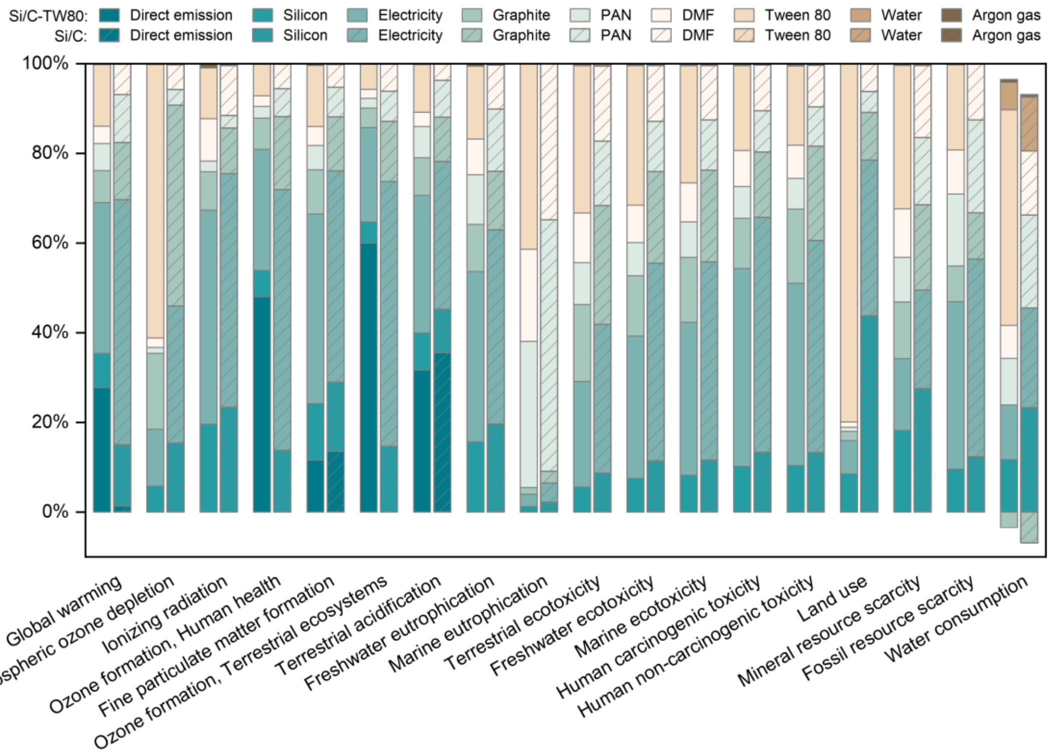

Figure S8. Contribution analysis of full-spectrum environmental categories of Tween-assisted battery cathode material preparation.

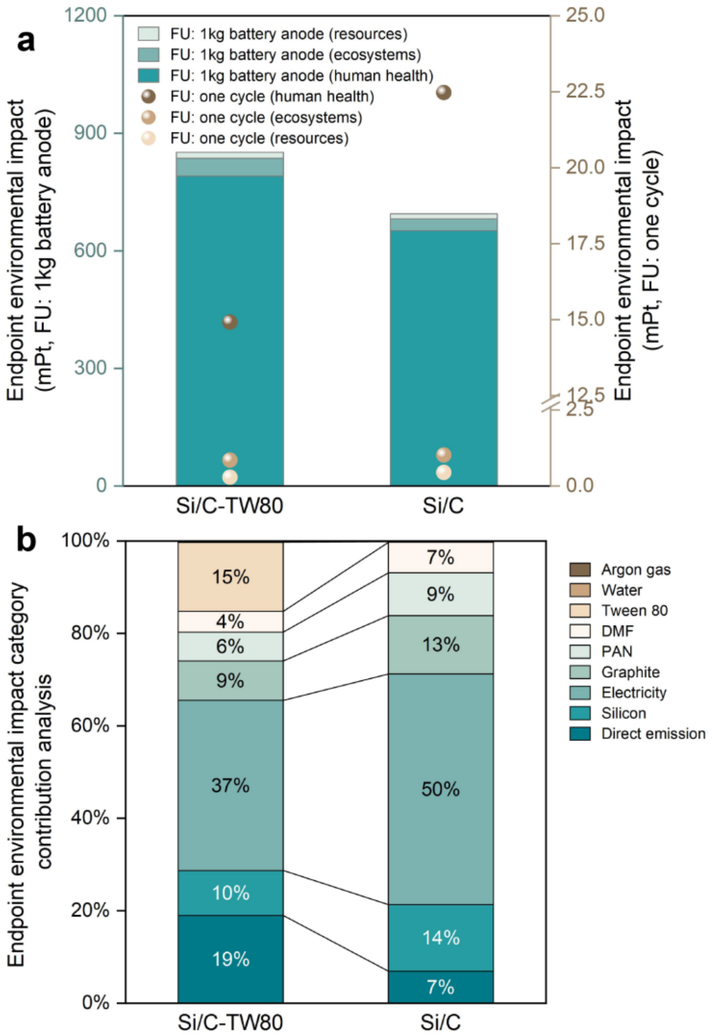

Figure S9. Analysis of endpoint environmental categories of Tween-assisted battery cathode material preparation.

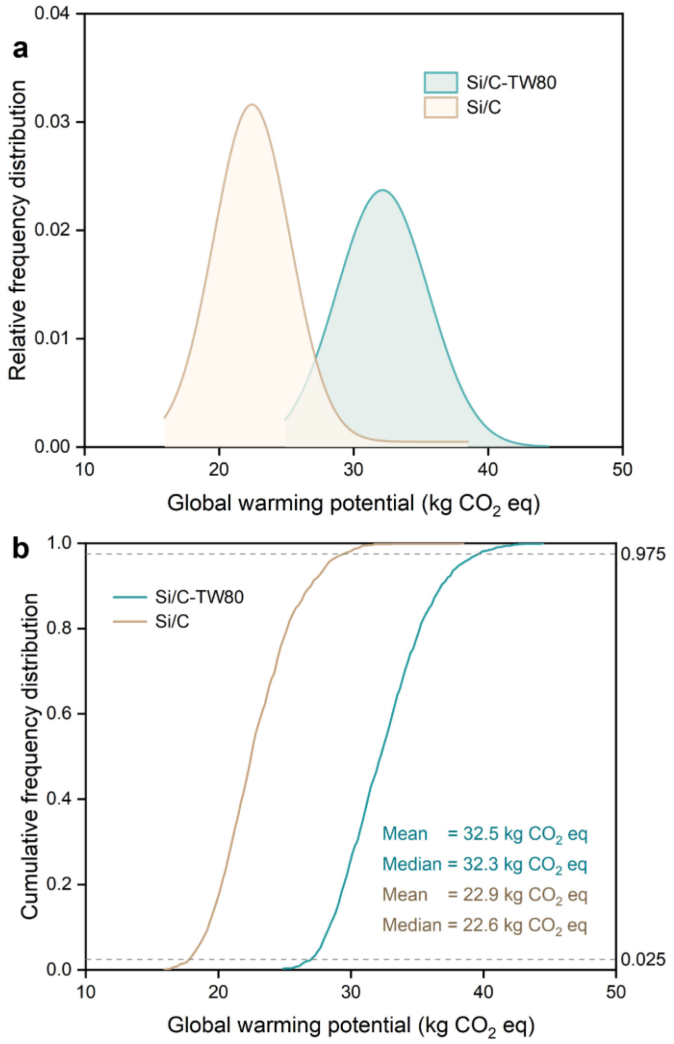

Figure S10. Uncertainty analysis of global warming potential of Tween-assisted battery cathode material preparation. (a) Relative frequency distribution and (b) cumulative frequency distribution for the production of 1 kg of the battery anode.

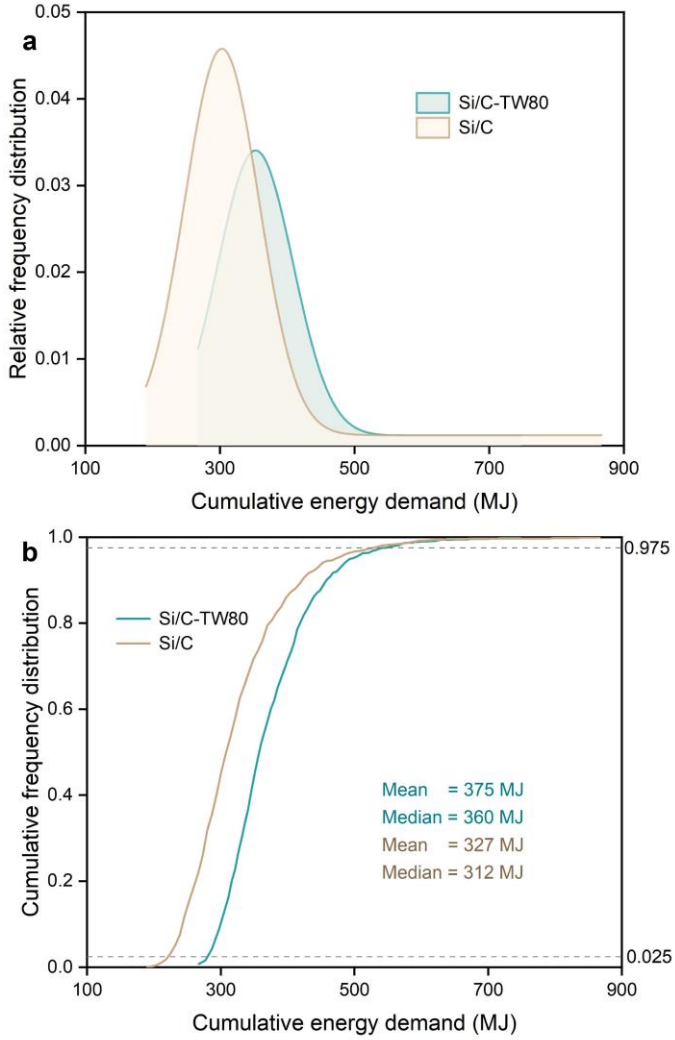

Figure S11. Uncertainty analysis of cumulative energy demand of Tween-assisted battery cathode material preparation. (a) Relative frequency distribution and (b) cumulative frequency distribution for the production of 1 kg of the battery anode.

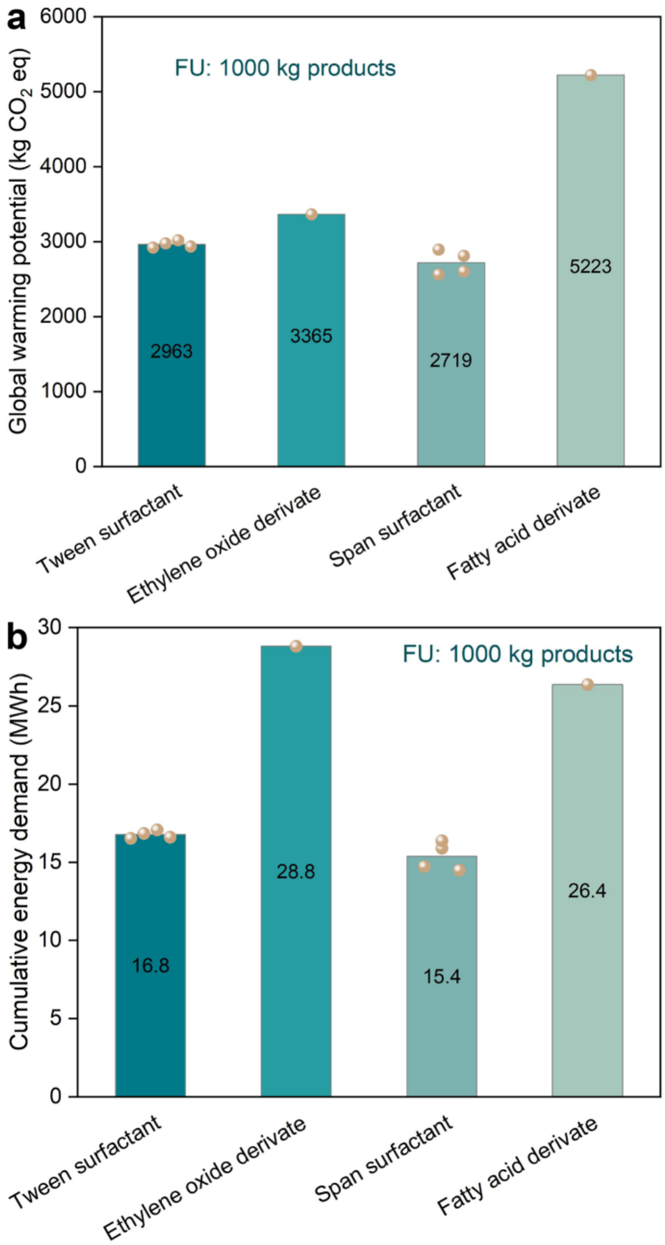

Figure S12. Comparison of global warming potential and cumulative energy demand reported in this study and the Ecoinvent database. Comparison of (a) global warming potential and (b) cumulative energy demand. Bar graphs represent averages. Scatter plots represent LCA results for the specified Tween or Span product. The Tween and Span products are benchmarked against the Ecoinvent database for ethylene oxide derivatives and fatty acid derivatives non-ionic surfactants, respectively. Information on plant construction in the Ecoinvent database was removed and the electricity structure was harmonised.

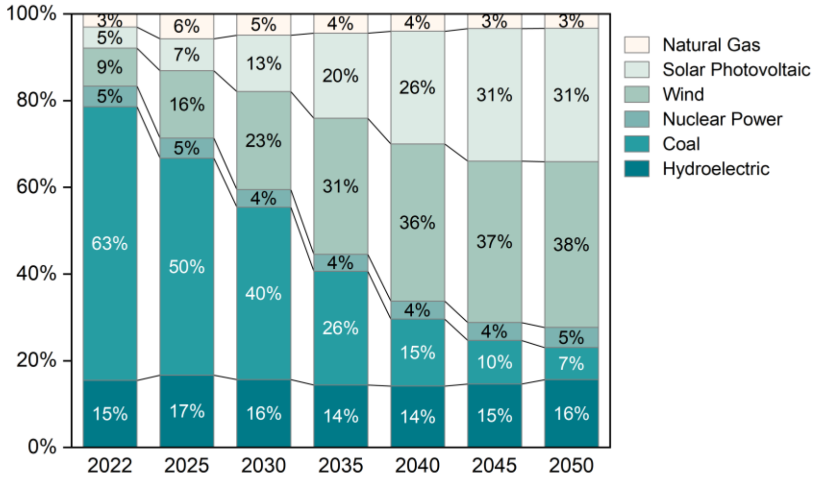

Figure S13. Evolution of the projected electricity mix in the Chinese grid from 2022 to 2050.

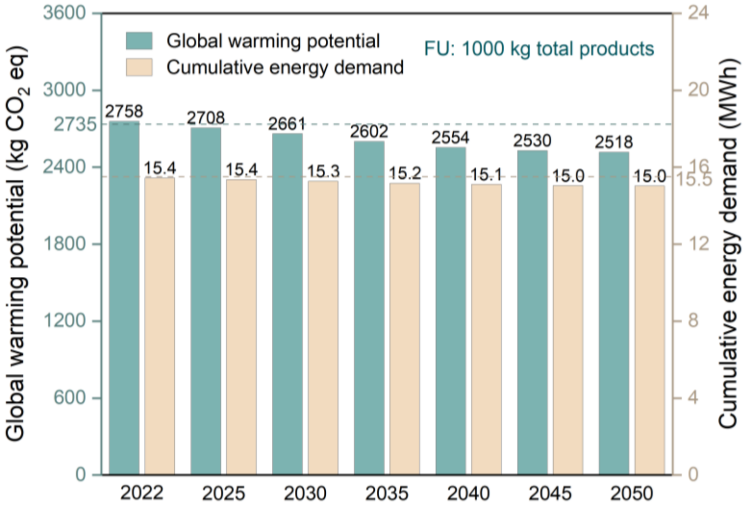

Figure S14. The global warming potential and cumulative energy demand for the production of 1,000 kg of the total product in China, 2022–2025. The blue and yellow dotted lines represent the global warming potential and cumulative energy demand for the production of 1,000 kg of total products, respectively.

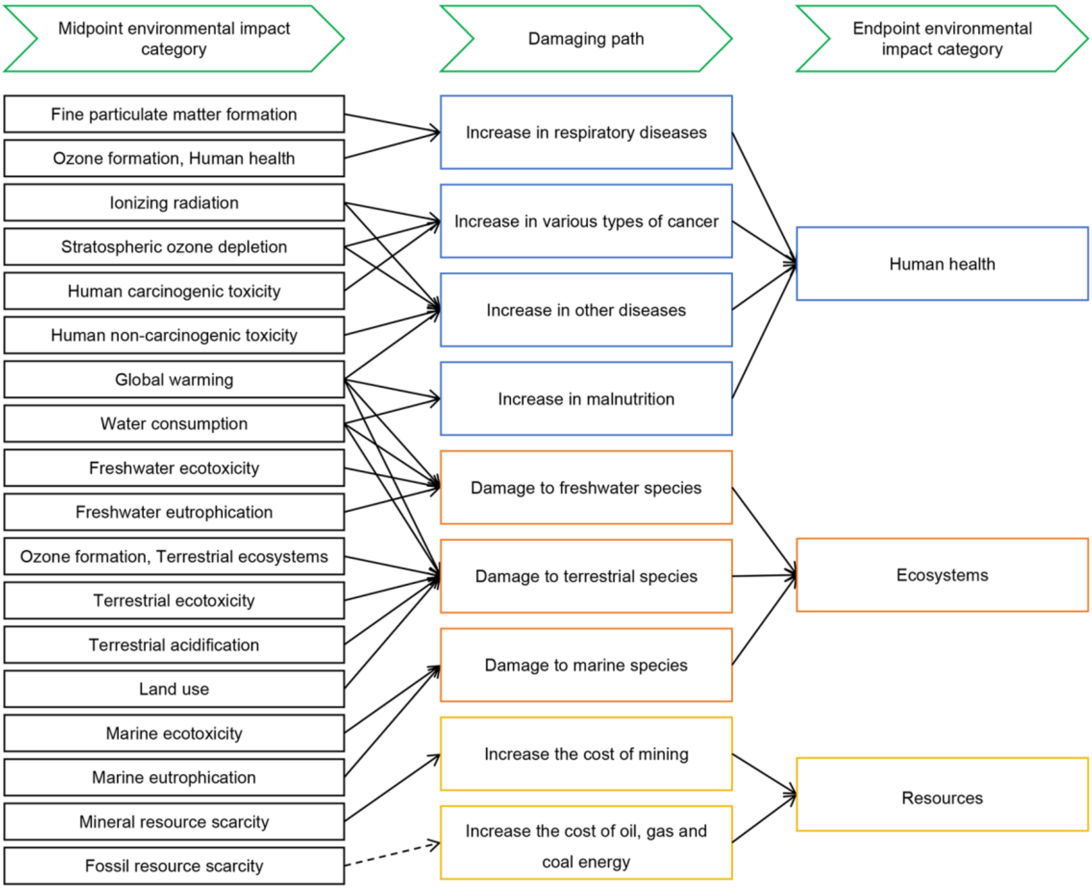

Figure S15. An overview diagram of the ReCiPe (H) 2016 method structure. The dotted line indicates that there is no constant midpoint to endpoint factor for fossil resources.

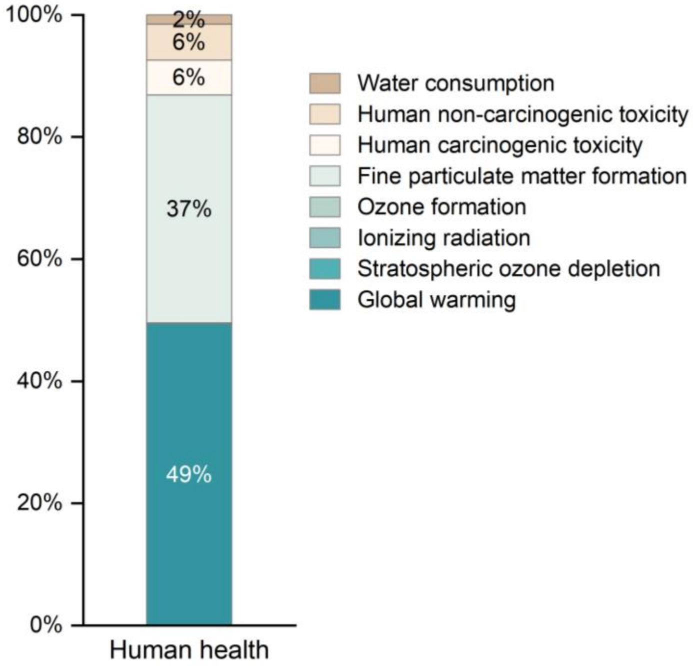

Figure S16. Analysis of the contribution of human health environmental impact categories.

Table S1. Summary of the physical and chemical properties of typical Tween and Span products.

Item	Span 20	Span 40	Span 60	Span 80	Tween 20	Tween 40	Tween 60	Tween 80
Color	Amber	Faint yellow	Faint yellow	Amber to brown	Faint yellow to yellow	Yellow to orange	Faint yellow	Faint yellow
Morphology	Viscous liquid	Wax-like substance	Powdered or lumpy solids	Viscous oily liquid	Viscous liquid	Viscous liquid or jelly-like substance	Paste-like substance	Oily substance
Fatty acid (wt.%)	56-68	63-71	71-75	73-77				
Polyol (wt.%)	36-49	33-38	29.5-33.5	28-32				
Acid value (in KOH, mg/g)	≤ 7	≤ 7	≤ 10	≤ 8	≤ 2	≤ 2	≤ 2	≤ 2
Saponification value (in KOH, mg/g)	155-170	140-155	147-157	145-160	40-50	41-52	45-55	45-55
Hydroxyl value (in KOH, mg/g)	330-360	270-305	235-260	193-210	96-108	90-107	81-96	65-80
Water content (wt.%)	≤ 1.5	≤ 1.5	≤ 1.5	≤ 2.0	≤ 3.0	≤ 3.0	≤ 3.0	≤ 3.0
Burned residue (wt.%)	≤ 0.50	≤ 0.50			≤ 0.25	≤ 0.25	≤ 0.25	≤ 0.25
Arsenic content (mg/kg)	≤ 3	≤ 3	≤ 3	≤ 3			≤ 3	≤ 3
Lead content (mg/kg)	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2
Oxyethylene group (in C_2H_4O, wt.%)					70.0-74.0	66.0-70.5	65.0-69.5	65.0-69.5

Table S2. Guide prices for Tween and Span products.

Product type	Unit	Guide price
Span 20	CNY/kg	17.0
Span 40	CNY/kg	17.5
Span 60	CNY/kg	15.8
Span 80	CNY/kg	15.5
Tween 20	CNY/kg	18.3
Tween 40	CNY/kg	18.0
Tween 60	CNY/kg	17.8
Tween 80	CNY/kg	17.7

Table S3. The inventory data for Tween and Span products.

Type	Item	Unit	Amount	Concerning process
Input	70 wt.% Sorbitol	kg	397.72	Rehydration reaction
	Stearic acid	kg	238	The esterification reaction of Span 60
	Oleic acid	kg	206	The esterification reaction of Span 80
	Palmitic acid	kg	7.9	The esterification reaction of Span 40
	Lauric acid	kg	17.9	The esterification reaction of Span 20
	Sodium hydroxide	kg	1.932	Esterification reaction, neutralization and pollution treatment
	85 wt.% Phosphoric acid	kg	1.317	Rehydration reaction
	Hydrogen peroxide	kg	0.936	Neutralization and decolorization
	Acetic acid	kg	0.480	Neutralization, decolorization, and examination
	Ethylene oxide	kg	271.58	Addition reaction
	Acetic anhydride	kg	0.0004	Examination
	Isopropanol	kg	0.0004	Examination
	Trichloromethane	kg	0.0006	Examination
	Ethanol	kg	0.0008	Examination
	Normal butanol	kg	0.001	Examination
	Nitric acid	kg	0.0006	Examination
	Natural gas	m^3	71.6	All processes (as energy)
	Biomass fuel	kg	4.8	All processes (as a backup energy source)
	Conduction oil	kg	0.3	All processes (heat transmission)
	Electricity	kWh	78	All processes (as energy)
	Water	kg	1713.74	All processes (net import)
	Activated carbon	kg	0.0212	For the treatment of exhaust gases and soft water preparation
Output as product	Span 20	kg	14.4	As liquid products, including Span-20
	Span 40	kg	10	As solid products, including Span-40
	Span 60	kg	312	As solid products, including Span-60 and Span-65
	Span 80	kg	263.6	As liquid products, including Span-80, Span-83, and Span-85

Table S3. The inventory data for Tween and Span products (Continued).

Type	Item	Unit	Amount	Concerning process
Output as product	Tween 20	kg	63	As liquid products, including Tween-20 and Tween-21
	Tween 40	kg	4	As liquid products, including Tween-40
	Tween 60	kg	164	As liquid products, including Tween-60, Tween-61, and Tween-65
	Tween 80	kg	169	As liquid products, including Tween-80, Tween-81, and Tween-85
Emission to air	Sulfur dioxide (SO_2)	kg	0.0143	From boiler combustion
	Nitrogen oxides (NO_x)	kg	0.0670	From boiler combustion
	Particulates (PM)	kg	0.0205	From boiler combustion and granulation processes
	Non-methane hydrocarbons (NMHC)	kg	0.00684	From esterification reaction, addition reaction, feeding process, and examination
	Carbon dioxide (CO_2)	kg	161.471	From boiler combustion
	Methane (CH_4)	kg	0.670	From boiler combustion
Waste to treatment	Wastewater treatment	kg	73.083	Mainly from domestic water
	Inert solid waste treatment	kg	0.0757	Mainly from boiler room, general solid waste
	Municipal solid waste	kg	0.48	From domestic garbage
	Waste plastic treatment	kg	0.912	Mainly from the packaging of input materials
	Hazardous waste treatment	kg	0.916	Mainly from fatty acid packaging bags

Notice:

1. A given range of Tween and Span products may include a main product and multiple sub-products. For example, the Span 60 series of products includes the Span-60 main product and the Span-65 sub-product. Since the process lines and feedstock types are the same for the same family of products, the LCI is no longer broken down into each type of sub-product.
2. The carbon dioxide and methane emission factors for natural gas combustion were taken as 2.162 kg/m^3 and 0.0389 g/m^3, respectively, while the carbon dioxide and methane emission factors for biomass combustion were taken as 100 kg/TJ and 10 kg/TJ, respectively.

Table S4. The inventory data for sorbitol.[11]

Type	Item	Unit	Amount
Input	Water	kg	1338.1
	Glucose	kg	692.3
	Raney nickel	kg	0.21
	Heat	MJ	2914.8
	Electricity	MJ	704.9
Output	70 wt.% Sorbitol	kg	1000

Table S5. The inventory data for biomass fuel.[12]

Type	Item	Unit	Amount
Input	Diesel, as energy	kg	1.48
	Electricity	kWh	72.2
	Nitrogen fertilizer	kg	1.55
	Phosphate fertilizer	kg	0.54
	Potassium fertilizer	kg	0.66
	Pesticide	kg	0.01
	Water	kg	31.4
	Polypropylene	kg	2.25
	Arable land occupation	m^2	122.24
	Land occupation	m^2	4
	Transport distance	tkm	15.51
Output	Biomass fuel	kg	1000
	Biomass ash	kg	2.6
	CH_4	g	1.76
	NMVOC	g	1.13
	CO	g	9.44
	NO_x	g	10.32
	PM_{10}	g	9.59
	SO_2	g	1.71

Notice: The calorific value of diesel as energy is taken as 45 MJ/kg. The calorific value of the produced biomass fuel is 13.9 MJ/kg.

Table S6. Data quality index evaluation matrix.[13]

Indicator	1	2	3	4	5
Reliability (U_1)	Verified data based on measurements (1.00)	Verified data partly based on assumptions or non-verified data based on measurements (1.05)	Non-verified data partly based on qualified estimates (1.10)	Qualified estimate (1.20)	Non-qualified estimate (1.50)
Completeness (U_2)	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuation (1.00)	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations (1.02)	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods (1.05)	Representative data from only one site relevant for the market considered or some sites but from shorter periods (1.10)	Representativeness unknown or data from a small number of sites and from shorter periods (1.20)
Temporal correlation (U_3)	Less than 3 years of difference to the time period of the dataset (1.00)	Less than 6 years of difference to the time period of the dataset (1.03)	Less than 10 years of difference to the time period of the dataset (1.10)	Less than 15 years of difference to the time period of the dataset (1.20)	Age of data unknown or more than 15 years of difference to the time period of the dataset (1.50)
Geographical correlation (U_4)	Data from area under study (1.00)	Average data from larger area in which area under study is included (1.01)	Data from area with similar production conditions (1.02)	Data from area with slightly similar production conditions (1.05)	Data from unknown or distinctly different area (1.10)
Further technological correlation (U_5)	Data from enterprises, processes and materials under study (1.00)	Data from processes and materials under study but from different enterprises (1.05)	Data from processes and materials under study but from different technologies (1.20)	Data on related processes or materials (1.50)	Data on related processes on laboratory scale or from different technologies (2.00)

Notice: The numbers in parentheses represent the corresponding uncertainty coefficients.

Table S7. The basic uncertainty coefficients of input and output data (U_b).[13]

Type	Input/output	Combustion emissions	Process emissions	Agricultural emissions
Demand input	Thermal energy, electricity, semi-finished products, working materials, and waste treatment	1.05	1.05	1.05
	Transport service	2.00	2.00	2.00
	Base installation	3.00	3.00	3.00
Resource input	Primary energy carriers, metals, and salts	1.05	1.05	1.05
	Land use (occupation)	1.50	1.50	1.50
	Land use (renovation)	2.00	2.00	2.00
Emission to air	CO_2	1.05	1.05	
	SO_2	1.05		
	NMVOC	1.50		
	NO_X、N_2O	1.50		1.40
	CH_4、NH_3	1.50		1.20
	Hydrocarbon monomer series	1.50	2.00	
	PM > 10	1.50	1.50	
	PM_{10}	2.00	2.00	
	$PM_{2.5}$	3.00	3.00	
	Polycyclic aromatic hydrocarbon	3.00		
	CO and heavy metals	5.00		
	Other inorganic emissions		1.50	
	Radionuclide		3.00	
Emission to water	BOD, COD, DOC, TOC, and inorganic compounds		1.50	
	Hydrocarbon monomer series and polycyclic aromatic hydrocarbon		3.00	
	Heavy metals		5.00	1.80
	Pesticides			1.50
	Phosphates and nitrates			1.50
Emission to soil	Petroleum		1.50	
	Heavy metals		1.50	1.50
	Pesticides			1.20

Table S8. Full-spectrum environmental impacts for the production of 1,000kg of the total products.

Impact category	Unit	Total impacts	Sorbitol	Stearic acid	Oleic acid	Palmitic acid	Lauric acid	Ethylene oxide	Natural gas	Electricity	Direct emission	Other
Global warming	kg CO_2 eq	2.80E+03	5.92E+02	1.31E+02	9.87E+02	3.79E+01	8.58E+01	6.66E+02	2.93E+01	6.91E+01	1.86E+02	1.09E+01
Stratospheric ozone depletion	kg CFC11 eq	5.03E-03	2.19E-03	4.07E-05	2.39E-03	9.15E-05	2.07E-04	9.40E-05	2.86E-06	1.06E-05	0.00E+00	6.22E-06
Ionizing radiation	kBq Co-60 eq	6.36E+01	2.58E+01	1.00E+01	4.70E+00	1.80E-01	4.08E-01	1.91E+01	1.57E-01	2.71E+00	0.00E+00	5.52E-01
Ozone formation, Human health	kg NO_x eq	4.90E+00	1.63E+00	3.92E-01	1.02E+00	3.90E-02	8.83E-02	1.31E+00	7.52E-02	1.91E-01	1.41E-01	2.36E-02
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.12E+00	9.86E-01	2.34E-01	8.47E-01	3.25E-02	7.36E-02	7.80E-01	1.31E-02	9.79E-02	3.24E-02	2.12E-02
Ozone formation, Terrestrial ecosystems	kg NO_x eq	5.07E+00	1.69E+00	4.05E-01	1.12E+00	4.30E-02	9.75E-02	1.40E+00	9.52E-02	1.91E-01	6.95E-03	2.48E-02
Terrestrial acidification	kg SO_2 eq	7.27E+00	2.77E+00	4.57E-01	1.65E+00	6.32E-02	1.43E-01	1.72E+00	2.92E-02	2.12E-01	1.76E-01	5.20E-02
Freshwater eutrophication	kg P eq	5.31E-01	1.97E-01	4.79E-02	1.05E-01	4.02E-03	9.10E-03	1.45E-01	1.92E-03	1.26E-02	0.00E+00	7.85E-03
Marine eutrophication	kg N eq	1.31E+00	2.70E-01	3.50E-03	9.09E-01	3.49E-02	7.90E-02	9.45E-03	1.67E-04	8.67E-04	0.00E+00	2.94E-03
Terrestrial ecotoxicity	kg 1,4-DCB	7.41E+03	3.21E+03	9.64E+02	1.85E+03	7.11E+01	1.61E+02	1.01E+03	1.70E+01	5.36E+01	0.00E+00	7.10E+01
Freshwater ecotoxicity	kg 1,4-DCB	1.02E+02	3.12E+01	9.21E+00	3.95E+01	1.51E+00	3.43E+00	1.51E+01	2.41E-01	1.06E+00	0.00E+00	1.15E+00
Marine ecotoxicity	kg 1,4-DCB	1.06E+02	3.93E+01	1.21E+01	2.77E+01	1.06E+00	2.41E+00	1.99E+01	3.35E-01	1.40E+00	0.00E+00	1.53E+00
Human carcinogenic toxicity	kg 1,4-DCB	9.07E+01	3.41E+01	1.04E+01	1.54E+01	5.91E-01	1.34E+00	2.25E+01	2.01E+00	2.14E+00	0.00E+00	2.28E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	1.35E+03	5.96E+02	1.75E+02	1.50E+02	5.74E+00	1.30E+01	3.48E+02	4.87E+00	3.14E+01	0.00E+00	2.62E+01
Land use	m^2a crop eq	9.77E+02	1.33E+02	3.64E+00	7.39E+02	2.84E+01	6.42E+01	5.55E+00	5.22E-01	9.17E-01	0.00E+00	1.16E+00
Mineral resource scarcity	kg Cu eq	6.64E+00	3.06E+00	7.18E-01	1.43E+00	5.49E-02	1.24E-01	1.03E+00	9.15E-02	3.36E-02	0.00E+00	9.65E-02
Fossil resource scarcity	kg oil eq	6.89E+02	1.42E+02	3.59E+01	4.01E+01	1.54E+00	3.48E+00	3.85E+02	6.51E+01	1.37E+01	0.00E+00	2.84E+00
Water consumption	m^3	7.13E+01	3.45E+01	1.04E+00	2.40E+01	9.19E-01	2.08E+00	6.71E+00	5.19E-02	1.83E-01	0.00E+00	1.85E+00

Table S9. Full-spectrum environmental impacts for the production of 1,000kg of the specified products.

Impact category	Unit	Span 20	Span 40	Span 60	Span 80	Tween 20	Tween 40	Tween 60	Tween 80
Global warming	kg CO_2 eq	2.87E+03	2.96E+03	2.66E+03	2.62E+03	3.08E+03	3.04E+03	3.00E+03	2.99E+03
Stratospheric ozone depletion	kg CFC11 eq	5.17E-03	5.32E-03	4.79E-03	4.71E-03	5.55E-03	5.47E-03	5.39E-03	5.37E-03
Ionizing radiation	kBq Co-60 eq	6.54E+01	6.73E+01	6.06E+01	5.96E+01	7.02E+01	6.92E+01	6.83E+01	6.80E+01
Ozone formation, Human health	kg NO_x eq	5.04E+00	5.19E+00	4.67E+00	4.60E+00	5.41E+00	5.34E+00	5.26E+00	5.24E+00
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.21E+00	3.30E+00	2.97E+00	2.92E+00	3.44E+00	3.39E+00	3.35E+00	3.33E+00
Ozone formation, Terrestrial ecosystems	kg NO_x eq	5.21E+00	5.36E+00	4.83E+00	4.75E+00	5.59E+00	5.52E+00	5.44E+00	5.41E+00
Terrestrial acidification	kg SO_2 eq	7.47E+00	7.69E+00	6.92E+00	6.81E+00	8.02E+00	7.91E+00	7.80E+00	7.76E+00
Freshwater eutrophication	kg P eq	5.45E-01	5.61E-01	5.05E-01	4.97E-01	5.85E-01	5.77E-01	5.69E-01	5.67E-01
Marine eutrophication	kg N eq	1.35E+00	1.39E+00	1.25E+00	1.23E+00	1.45E+00	1.43E+00	1.41E+00	1.40E+00
Terrestrial ecotoxicity	kg 1,4-DCB	7.62E+03	7.84E+03	7.06E+03	6.95E+03	8.18E+03	8.07E+03	7.95E+03	7.92E+03
Freshwater ecotoxicity	kg 1,4-DCB	1.05E+02	1.08E+02	9.75E+01	9.60E+01	1.13E+02	1.11E+02	1.10E+02	1.09E+02
Marine ecotoxicity	kg 1,4-DCB	1.09E+02	1.12E+02	1.01E+02	9.92E+01	1.17E+02	1.15E+02	1.14E+02	1.13E+02
Human carcinogenic toxicity	kg 1,4-DCB	9.33E+01	9.60E+01	8.64E+01	8.50E+01	1.00E+02	9.88E+01	9.74E+01	9.69E+01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E+03	1.43E+03	1.29E+03	1.26E+03	1.49E+03	1.47E+03	1.45E+03	1.44E+03
Land use	m^2a crop eq	1.00E+03	1.03E+03	9.30E+02	9.15E+02	1.08E+03	1.06E+03	1.05E+03	1.04E+03
Mineral resource scarcity	kg Cu eq	6.82E+00	7.02E+00	6.32E+00	6.22E+00	7.32E+00	7.22E+00	7.12E+00	7.09E+00
Fossil resource scarcity	kg oil eq	7.09E+02	7.30E+02	6.57E+02	6.46E+02	7.61E+02	7.50E+02	7.40E+02	7.36E+02
Water consumption	m^3	7.33E+01	7.54E+01	6.79E+01	6.68E+01	7.86E+01	7.76E+01	7.65E+01	7.61E+01

Table S10. Normalised baseline values (based on 2010 world emissions in the ReCiPe (H) 2016 method).

Number	Impact category	Unit	Baseline value
1	Global warming	kg CO_2 eq	8000
2	Stratospheric ozone depletion	kg CFC-11 eq	0.060
3	Ionizing radiation	kBq Co-60 eq	480.77
4	Ozone formation, Human health	kg NO_x eq	20.58
5	Fine particulate matter formation	kg $PM_{2.5}$ eq	25.58
6	Ozone formation, Terrestrial ecosystems	kg NO_x eq	17.76
7	Terrestrial acidification	kg SO_2 eq	40.98
8	Freshwater eutrophication	kg P eq	0.65
9	Marine eutrophication	kg N eq	4.61
10	Terrestrial ecotoxicity	kg 1,4-DCB	15197.57
11	Freshwater ecotoxicity	kg 1,4-DCB	25.19
12	Marine ecotoxicity	kg 1,4-DCB	43.48
13	Human carcinogenic toxicity	kg 1,4-DCB	10.30
14	Human non-carcinogenic toxicity	kg 1,4-DCB	31250
15	Land use	m^2a crop eq	6172.84
16	Mineral resource scarcity	kg Cu eq	120048.02
17	Fossil resource scarcity	kg oil eq	980.39
18	Water consumption	m^3	266.67

Table S11. The endpoint environmental impacts for the production of 1,000 kg of the total products.

Item	Human health	Ecosystems	Resources	Total impacts
Sorbitol	1.83E+01	1.11E+00	4.41E-01	1.99E+01
Stearic acid	4.32E+00	1.65E-01	1.07E-01	4.59E+00
Oleic acid	1.94E+01	2.72E+00	1.34E-01	2.23E+01
Palmitic acid	7.45E-01	1.04E-01	5.14E-03	8.55E-01
Lauric acid	1.69E+00	2.37E-01	1.16E-02	1.94E+00
Ethylene oxide	1.60E+01	7.20E-01	1.54E+00	1.82E+01
Natural gas	5.42E-01	2.91E-02	2.49E-01	8.20E-01
Electricity	1.75E+00	7.63E-02	1.56E-02	1.85E+00
Direct emission	2.40E+00	1.50E-01	0.00E+00	2.55E+00
Other	4.81E-01	1.92E-02	9.75E-03	5.10E-01
Total impacts	6.57E+01	5.34E+00	2.51E+00	7.35E+01

Table S12. The endpoint environmental impacts for the production of 1,000 kg of the specified products.

Product type	Human health	Ecosystems	Resources	Total impacts
Span 20	6.75E+01	5.49E+00	2.58E+00	7.56E+01
Span 40	6.95E+01	5.65E+00	2.66E+00	7.78E+01
Span 60	6.25E+01	5.08E+00	2.39E+00	7.00E+01
Span 80	6.16E+01	5.00E+00	2.36E+00	6.89E+01
Tween 20	7.25E+01	5.89E+00	2.77E+00	8.11E+01
Tween 40	7.15E+01	5.81E+00	2.74E+00	8.00E+01
Tween 60	7.05E+01	5.73E+00	2.70E+00	7.89E+01
Tween 80	7.02E+01	5.70E+00	2.68E+00	7.85E+01

Table S13. Quality assessment of inventory data for uncertainty analysis.

Indicator	Details of data quality assessment	Uncertainty coefficient
Reliability (U_1)	1. Input (all) and output (Waste): verified data based on measurements 2. Output (SO_2, NO_x, PM, NMHC, and wastewater): verified data partly based on assumptions 3. Output (CO_2 and CH_4): non-verified data partly based on qualified estimates	1/1.05/1
Completeness (U_2)	1. Representative data from only one site relevant for the market is considered	1.1
Temporal correlation (U_3)	1. Less than 3 years of difference from the time period of the dataset	1
Geographical correlation (U_4)	1. Data from area under study	1
Further technological correlation (U_5)	1. Data from enterprises under study	1
Basic uncertainty (U_b)	1. Input (all) and output (SO_2, CO_2, wastewater, and waste) 2. Output (NO_x, PM, NMHC, and CH_4)	1.05/1.5

Table S14. Geometric SD of inventory data for uncertainty analysis.

Item	Best possible SD	Worst possible SD	This study
Input (all) and output (waste)	1.05	2.52	1.11
Output (SO_2 and wastewater)	1.05	2.52	1.12
Output (CO_2)	1.05	2.52	1.15
Output (NO_x, PM, and NMHC)	1.50	2.74	1.52
Output (CH_4)	1.50	2.74	1.53

Table S15. Summary of uncertainty analyses of global warming potential and cumulative energy demand (FU: 1,000 kg products).

Impact category	Product type	Mean	Median	Standard deviation	Coefficient of variation (%)	Min (2.5% Percentile)	Max (97.5% Percentile)
Global warming potential ($kg\ CO_2\ eq$)	Total products	2.73E+03	2.72E+03	3.18E+02	1.17E+01	2.14E+03	3.39E+03
	Span 20	2.83E+03	2.82E+03	3.44E+02	1.21E+01	2.23E+03	3.56E+03
	Span 40	2.87E+03	2.85E+03	3.49E+02	1.22E+01	2.24E+03	3.65E+03
	Span 60	2.61E+03	2.59E+03	3.02E+02	1.16E+01	2.08E+03	3.29E+03
	Span 80	2.59E+03	2.55E+03	3.17E+02	1.22E+01	2.05E+03	3.30E+03
	Tween 20	3.03E+03	3.02E+03	3.76E+02	1.24E+01	2.35E+03	3.86E+03
	Tween 40	2.98E+03	2.95E+03	3.62E+02	1.22E+01	2.33E+03	3.80E+03
	Tween 60	2.92E+03	2.89E+03	3.51E+02	1.20E+01	2.27E+03	3.67E+03
	Tween 80	2.92E+03	2.90E+03	3.63E+02	1.24E+01	2.28E+03	3.68E+03
Cumulative energy demand (MJ)	Total products	5.56E+04	5.52E+04	5.59E+03	1.01E+01	4.54E+04	6.76E+04
	Span 20	5.71E+04	5.69E+04	5.72E+03	1.00E+01	4.60E+04	6.95E+04
	Span 40	5.91E+04	5.86E+04	6.20E+03	1.05E+01	4.81E+04	7.33E+04
	Span 60	5.31E+04	5.27E+04	5.29E+03	9.95E+00	4.37E+04	6.42E+04
	Span 80	5.24E+04	5.21E+04	5.28E+03	1.01E+01	4.33E+04	6.38E+04
	Tween 20	6.14E+04	6.06E+04	6.39E+03	1.04E+01	5.05E+04	7.57E+04
	Tween 40	6.07E+04	6.02E+04	6.28E+03	1.04E+01	4.95E+04	7.44E+04
	Tween 60	5.98E+04	5.97E+04	6.08E+03	1.02E+01	4.84E+04	7.27E+04
	Tween 80	5.96E+04	5.94E+04	5.81E+03	9.76E+00	4.94E+04	7.19E+04

Table S16. Summary of uncertainty analyses of full-spectrum environmental categories (FU: 1,000 kg total products).

Impact category	Unit	Mean	Median	Standard deviation	Coefficient of variation (%)	Min (2.5% Percentile)	Max (97.5% Percentile)
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.11E+00	3.08E+00	3.00E-01	9.66E+00	2.62E+00	3.76E+00
Fossil resource scarcity	kg oil eq	6.89E+02	6.77E+02	9.53E+01	1.38E+01	5.31E+02	8.94E+02
Freshwater ecotoxicity	kg 1,4-DCB	1.02E+02	9.80E+01	7.93E+01	7.76E+01	-4.04E+01	2.83E+02
Freshwater eutrophication	kg P eq	5.32E-01	4.87E-01	1.97E-01	3.71E+01	2.91E-01	1.05E+00
Global warming	kg CO_2 eq	2.79E+03	2.76E+03	3.44E+02	1.23E+01	2.18E+03	3.56E+03
Human carcinogenic toxicity	kg 1,4-DCB	2.60E+01	3.77E+01	2.05E+03	7.87E+03	-4.49E+03	4.21E+03
Human non-carcinogenic toxicity	kg 1,4-DCB	-7.02E+04	-2.44E+04	1.80E+06	-2.56E+03	-3.98E+06	3.53E+06
Ionizing radiation	kBq Co-60 eq	5.96E+01	3.65E+01	7.29E+01	1.22E+02	7.73E+00	2.90E+02
Land use	m^2a crop eq	9.64E+02	9.41E+02	1.88E+02	1.95E+01	6.70E+02	1.41E+03
Marine ecotoxicity	kg 1,4-DCB	1.06E+02	1.01E+02	6.00E+01	5.65E+01	-3.72E+00	2.43E+02
Marine eutrophication	kg N eq	1.30E+00	1.27E+00	2.60E-01	2.00E+01	8.96E-01	1.92E+00
Mineral resource scarcity	kg Cu eq	6.65E+00	6.27E+00	1.90E+00	2.86E+01	4.16E+00	1.17E+01
Ozone formation, Human health	kg NO_x eq	4.88E+00	4.85E+00	3.91E-01	8.00E+00	4.19E+00	5.66E+00
Ozone formation, Terrestrial ecosystems	kg NO_x eq	5.05E+00	5.01E+00	4.13E-01	8.18E+00	4.31E+00	5.87E+00
Stratospheric ozone depletion	kg CFC11 eq	4.99E-03	4.91E-03	7.89E-04	1.58E+01	3.66E-03	6.81E-03
Terrestrial acidification	kg SO_2 eq	7.25E+00	7.17E+00	6.88E-01	9.49E+00	6.01E+00	8.74E+00
Terrestrial ecotoxicity	kg 1,4-DCB	7.53E+03	6.82E+03	3.12E+03	4.15E+01	4.30E+03	1.52E+04
Water consumption	m^3	5.75E+01	7.37E+01	7.03E+02	1.22E+03	-1.29E+03	1.36E+03

Table S17. The application of Tween and Span products in the field of batteries.

Surfactant type	Battery type	Application	Detail	Source
Span-80 and Tween-80	LIB	Anode	Assist in the preparation of silicon-based anodes	[2]
Tween-80	SIB	Anode	Assist in the preparation of sodium anode	[14]
Tween-80	LIB	Anode	Assist in the preparation of CuO nanostructured anode	[15]
Tween-80	LIB	Anode	Assist in the preparation of SnO_2 nanostructured anodes	[16]
Tween-80	LIB	Anode	Preparation of SnO_2-TiO_2 nanocomposite structure anodes assisted by surfactants	[17]
Tween-80	LIB	Anode	Surfactant-assisted synthesis of high-conductivity silicon-carbon composites	[18]
Span-80	LIB	Anode	Surfactant-assisted synthesis of cobalt ferrite samples	[19]
Tween-80	LIB	Cathode	Assist in the preparation of lithium cobalt oxides	[20]
Tween-40	LIB	Cathode	Assist in the preparation of $LiFePO_4$/C cathode	[21]
Tween-80	LIB	Cathode	$LiFePO_4$ nanoparticles growth with preferential face modulated by surfactant	[3]
Tween-80	LIB	Cathode	Surfactant-assisted preparation of highly electrochemical $LiFePO_4$/C	[22]
Tween-80	LIB	Cathode	Surfactant-assisted synthesis of $LiFePO_4$/C nanocomposites	[23]
Span-80	SIB	Cathode	Surfactant-assisted synthesis of $Na_3V_2(PO_4)_3$ nanoflakes	[24]
Span-20	LIB	Cathode	Surfactant-assisted synthesis of Li_2FeSiO_4/C Cathode	[25]
Tween-20	ZIB	Electrolyte	Investigated surfactants change the morphology of zinc deposit	[26]
Tween-20	ZIB	Electrolyte	Surfactants used as electrolyte additives achieve highly stable zinc anodes	[27]
Tween-80	ZIB	Electrolyte	Surfactant facilitates stable zinc deposition	[28]
Tween-20	ZIB	Electrolyte	PEG 600 and Tween-20 synergistically reduce zinc corrosion	[29]
Tween-20	ZAB	Electrolyte	Improved electrochemical performance of ZAB by electrolyte additives	[30]
Tween-80	LSB	Separator	Surfactant-assisted preparation of nano-SiO_2-modified polypropylene separators	[31]
Tween-20	LIB	Thermal runaway	The water mist with added surfactants effectively cools the battery and reduces thermal runaway damage	[32]
Tween-20	LIB	Thermal runaway	The inhibitory effect of fine water mist with surfactants on battery thermal runaway was studied	[33]

Table S18. The inventory data of Tween-assisted battery cathode material preparation.

Substance	**Unit**	**Si/C-TW80**	**Si/C**
Input			
Si	kg	0.24	0.29
Electricity	kWh	13.25	14.65
Graphite	kg	0.24	0.29
Polyacrylonitrile	kg	0.48	0.58
DMF	kg	7.26	8.65
Tween 80	kg	1.61	
Deionized water	kg	322.48	386.39
Ar	kg	0.026	0.012
Output			
Si/C-TW80 (Si/C)	kg	1	1
Deionized water (recycling)	kg	306.35	367.07
DMF (recycling)	kg	6.89	8.22
HCN	kg	0.059	0.07
CO_2	kg	0.68	0.039
CO	kg	0.012	0.014
NH_3	kg	0.019	0.022
CH_4	kg	0.25	0.008
NMVOC	kg	0.32	

Table S19. Summary of uncertainty analyses of global warming potential and cumulative energy demand for Tween-assisted battery cathode material preparation.

Statistical indicator	**Global warming potential ($kg\ CO_2\ eq$)**	**Cumulative energy demand (MJ)**

	Si/C-TW80	**Si/C**	**Si/C-TW80**	**Si/C**
Mean	3.25E+01	2.29E+01	3.75E+02	3.27E+02
Median	3.23E+01	2.26E+01	3.60E+02	3.12E+02
Standard deviation	3.30E+00	3.00E+00	6.87E+01	7.94E+01
Coefficient of variation (%)	1.02E+01	1.31E+01	1.83E+01	2.42E+01
Min (2.5% Percentile)	2.71E+01	1.79E+01	2.82E+02	2.25E+02
Max (97.5% Percentile)	3.98E+01	2.96E+01	5.51E+02	5.33E+02

Table S20. Summary of uncertainty analyses of full-spectrum environmental categories for Tween-assisted battery cathode material preparation.

Impact category	Type	Mean	Median	Standard deviation	Coefficient of variation (%)	Min (2.5% Percentile)	Max (97.5% Percentile)
Fine particulate matter formation	Si/C-TW80	3.95E-02	3.85E-02	5.26E-03	1.33E+01	3.15E-02	5.13E-02
(kg $PM_{2.5}$ eq)	Si/C	3.91E-02	3.83E-02	5.05E-03	1.29E+01	3.14E-02	5.09E-02
Fossil resource scarcity	Si/C-TW80	6.24E+00	5.96E+00	1.44E+00	2.31E+01	4.27E+00	9.75E+00
(kg oil eq)	Si/C	5.85E+00	5.48E+00	1.76E+00	3.01E+01	3.71E+00	1.03E+01
Freshwater ecotoxicity	Si/C-TW80	5.71E-01	5.42E-01	2.07E-01	3.63E+01	2.56E-01	1.02E+00
(kg 1,4-DCB)	Si/C	4.42E-01	4.13E-01	1.60E-01	3.61E+01	2.76E-01	7.56E-01
Freshwater eutrophication	Si/C-TW80	5.69E-03	4.75E-03	3.35E-03	5.89E+01	2.42E-03	1.37E-02
(kg P eq)	Si/C	5.36E-03	4.58E-03	3.07E-03	5.73E+01	2.19E-03	1.29E-02
Global warming	Si/C-TW80	3.50E+01	3.48E+01	3.44E+00	9.83E+00	2.90E+01	4.24E+01
(kg CO_2 eq)	Si/C	2.38E+01	2.35E+01	3.15E+00	1.33E+01	1.86E+01	3.13E+01
Human carcinogenic toxicity	Si/C-TW80	1.03E+00	9.86E-01	3.59E+00	3.49E+02	-6.24E+00	8.44E+00
(kg 1,4-DCB)	Si/C	7.93E-01	6.40E-01	1.19E+00	1.50E+02	-2.01E-01	2.21E+00
Human non-carcinogenic toxicity	Si/C-TW80	1.72E+02	1.14E+02	3.09E+03	1.80E+03	-6.02E+03	6.51E+03
(kg 1,4-DCB)	Si/C	1.71E+01	1.43E+01	3.07E+02	1.80E+03	-5.66E+02	6.17E+02
Ionizing radiation	Si/C-TW80	9.71E-01	5.35E-01	1.40E+00	1.44E+02	1.16E-01	4.72E+00
(kBq Co-60 eq)	Si/C	9.91E-01	5.38E-01	1.32E+00	1.34E+02	1.20E-01	4.47E+00
Land use	Si/C-TW80	2.12E+00	2.09E+00	3.81E-01	1.80E+01	1.48E+00	3.00E+00
(m^2a crop eq)	Si/C	4.90E-01	4.72E-01	1.82E-01	3.71E+01	1.84E-01	9.31E-01

Table S20. Summary of uncertainty analyses of full-spectrum environmental categories for Tween-assisted battery cathode material preparation (Continued).

Impact category	Type	Mean	Median	Standard deviation	Coefficient of variation (%)	Min (2.5% Percentile)	Max (97.5% Percentile)
Marine ecotoxicity	Si/C-TW80	7.04E-01	6.63E-01	2.32E-01	3.30E+01	4.18E-01	1.23E+00
(kg 1,4-DCB)	Si/C	5.84E-01	5.39E-01	2.22E-01	3.80E+01	3.64E-01	1.03E+00
Marine eutrophication	Si/C-TW80	5.46E-03	5.32E-03	9.07E-04	1.66E+01	4.05E-03	7.47E-03
(kg N eq)	Si/C	3.82E-03	3.68E-03	9.42E-04	2.46E+01	2.35E-03	6.12E-03
Mineral resource scarcity	Si/C-TW80	3.62E-02	3.52E-02	6.18E-03	1.71E+01	2.67E-02	5.10E-02
(kg Cu eq)	Si/C	2.88E-02	2.82E-02	4.50E-03	1.56E+01	2.12E-02	3.94E-02
Ozone formation, Human health	Si/C-TW80	1.20E-01	1.18E-01	1.72E-02	1.44E+01	9.09E-02	1.59E-01
(kg NO_x eq)	Si/C	6.21E-02	6.01E-02	1.22E-02	1.96E+01	4.37E-02	9.03E-02
Ozone formation, Terrestrial ecosystems	Si/C-TW80	1.55E-01	1.52E-01	2.43E-02	1.57E+01	1.14E-01	2.12E-01
(kg NO_x eq)	Si/C	6.14E-02	5.94E-02	1.22E-02	1.99E+01	4.30E-02	8.94E-02
Stratospheric ozone depletion	Si/C-TW80	1.42E-05	1.41E-05	1.58E-06	1.11E+01	1.13E-05	1.75E-05
(kg CFC11 eq)	Si/C	6.49E-06	6.40E-06	8.82E-07	1.36E+01	5.06E-06	8.38E-06
Terrestrial acidification	Si/C-TW80	1.18E-01	1.17E-01	1.22E-02	1.04E+01	9.56E-02	1.45E-01
(kg SO_2 eq)	Si/C	1.21E-01	1.20E-01	1.38E-02	1.14E+01	9.80E-02	1.51E-01
Terrestrial ecotoxicity	Si/C-TW80	3.91E+01	3.70E+01	1.03E+01	2.64E+01	2.59E+01	6.56E+01
(kg 1,4-DCB)	Si/C	3.00E+01	2.85E+01	7.12E+00	2.38E+01	2.00E+01	4.63E+01
Water consumption	Si/C-TW80	9.45E-01	4.73E+00	4.51E+01	4.77E+03	-9.94E+01	8.10E+01
(m^3)	Si/C	2.03E+00	6.77E+00	5.19E+01	2.56E+03	-1.24E+02	8.89E+01

Table S21. Characterization factors of material and energy.

Item	Value	Unit	GWP 100	CED	ReCiPe Midpoint (H)																	
					GWP	ODP	IRP	OFHH	PMFP	OFTE	TAP	FEP	MEP	TEP	FETP	METP	HTPc	HTPcn	LUP	SOP	FFP	WCP
Electricity, United States	1	kWh	5.56E-01	1.13E+01	5.69E-01	9.81E-08	1.31E-01	9.65E-04	4.06E-04	1.01E-03	8.91E-04	5.29E-05	6.08E-06	4.66E-01	9.83E-03	1.26E-02	1.40E-02	1.65E-01	5.44E-03	5.73E-04	1.74E-01	1.85E-03
Electricity, China	1	kWh	8.57E-01	1.01E+01	8.85E-01	1.35E-07	3.48E-02	2.44E-03	1.25E-03	2.45E-03	2.72E-03	1.61E-04	1.11E-05	6.87E-01	1.35E-02	1.80E-02	2.74E-02	4.02E-01	1.17E-02	4.31E-04	1.76E-01	2.35E-03
Electricity, United Kingdom	1	kWh	3.35E-01	9.57E+00	3.41E-01	6.48E-08	1.17E-01	3.83E-04	1.27E-04	4.23E-04	2.93E-04	2.22E-05	3.84E-06	7.31E-01	2.28E-02	2.80E-02	1.19E-02	1.38E-01	3.45E-03	8.26E-04	1.25E-01	1.36E-03
Electricity, France	1	kWh	5.87E-02	1.08E+01	5.98E-02	1.40E-08	4.64E-01	8.97E-05	4.52E-05	9.74E-05	8.63E-05	8.70E-06	8.96E-06	4.23E-01	8.07E-03	1.01E-02	5.30E-03	9.79E-02	1.81E-03	6.96E-04	2.13E-02	2.23E-03
Electricity, Germany	1	kWh	5.57E-01	8.70E+00	5.73E-01	9.54E-08	1.28E-02	1.33E-03	6.60E-04	1.35E-03	1.44E-03	9.14E-05	6.41E-06	9.72E-01	2.49E-02	3.13E-02	2.10E-02	2.88E-01	9.58E-03	7.59E-04	1.40E-01	1.73E-03
Electricity, India	1	kWh	9.99E-01	1.08E+01	1.03E+00	1.57E-07	2.00E-02	2.85E-03	1.46E-03	2.86E-03	3.17E-03	1.87E-04	1.25E-05	7.12E-01	1.23E-02	1.67E-02	3.09E-02	4.54E-01	1.37E-02	3.98E-04	2.04E-01	2.64E-03
70 wt.% Sorbitol, see Table S4	1	kg	1.45E+00	3.11E+01	1.49E+00	5.50E-06	6.49E-02	4.10E-03	2.48E-03	4.24E-03	6.95E-03	4.95E-04	6.78E-04	8.07E+00	7.85E-02	9.89E-02	8.57E-02	1.50E+00	3.34E-01	7.68E-03	3.56E-01	8.66E-02
Stearic acid {GLO}| market | Cut-off, U	1	kg	5.41E-01	8.32E+00	5.52E-01	1.71E-07	4.21E-02	1.65E-03	9.85E-04	1.70E-03	1.92E-03	2.01E-04	1.47E-05	4.05E+00	3.87E-02	5.09E-02	4.36E-02	7.34E-01	1.53E-02	3.02E-03	1.51E-01	4.38E-03
Fatty acid {GLO}| market | Cut-off, U (Oleic acid, Palmitic acid, and lauric acid)	1	kg	4.74E+00	8.09E+01	4.79E+00	1.16E-05	2.28E-02	4.93E-03	4.11E-03	5.45E-03	8.00E-03	5.09E-04	4.41E-03	9.00E+00	1.92E-01	1.35E-01	7.48E-02	7.26E-01	3.59E+00	6.95E-03	1.94E-01	1.16E-01
Sodium hydroxide {GLO}| market | Cut-off, U	1	kg	1.29E+00	1.95E+01	1.32E+00	1.33E-06	1.47E-01	3.52E-03	2.69E-03	3.60E-03	4.85E-03	6.16E-04	5.51E-05	5.82E+00	6.91E-02	9.10E-02	8.66E-02	1.54E+00	3.17E-02	4.59E-03	3.20E-01	3.14E-02
85 wt.% Phosphoric acid (Phosphoric acid, industrial grade {GLO}| market | Cut-off, U; Water, decarbonised {CN}| market | Cut-off, U)	1	kg	1.17E+00	1.49E+01	1.19E+00	3.52E-07	5.24E-02	3.85E-03	6.94E-03	3.98E-03	2.12E-02	1.62E-03	4.56E-05	3.34E+01	3.43E-01	4.57E-01	9.82E-01	7.19E+00	3.12E-01	5.74E-02	2.76E-01	1.04E-01
Hydrogen peroxide {RoW}| market | Cut-off, U	1	kg	1.53E+00	2.34E+01	1.58E+00	3.56E-07	5.62E-02	3.28E-03	2.24E-03	3.49E-03	4.47E-03	5.82E-04	1.02E-04	6.87E+00	9.01E-02	1.20E-01	1.98E-01	1.91E+00	2.34E-02	4.53E-03	4.63E-01	7.48E-02
Acetic acid {GLO}| market | Cut-off, U	1	kg	2.22E+00	5.67E+01	2.32E+00	6.04E-07	1.76E-01	5.73E-03	3.49E-03	6.30E-03	6.78E-03	7.43E-04	7.43E-05	7.09E+00	8.22E-02	1.09E-01	1.18E-01	1.80E+00	4.80E-02	6.24E-03	1.11E+00	5.69E-02
Ethylene oxide {RoW}| market | Cut-off, U	1	kg	2.38E+00	6.88E+01	2.45E+00	3.46E-07	7.03E-02	4.82E-03	2.87E-03	5.14E-03	6.34E-03	5.35E-04	3.48E-05	3.71E+00	5.55E-02	7.31E-02	8.29E-02	1.28E+00	2.04E-02	3.79E-03	1.42E+00	2.47E-02
Acetic anhydride {GLO}| market | Cut-off, U	1	kg	4.17E+00	8.44E+01	4.30E+00	9.50E-07	2.41E-01	9.50E-03	5.88E-03	1.03E-02	1.23E-02	1.71E-03	1.05E-04	1.25E+01	1.56E-01	1.98E-01	1.92E-01	3.10E+00	9.15E-02	1.10E-02	1.65E+00	1.98E-01
Isopropanol {RoW}| market | Cut-off, U	1	kg	2.36E+00	6.63E+01	2.43E+00	2.91E-07	3.06E-02	5.23E-03	2.79E-03	5.89E-03	7.65E-03	6.05E-04	3.03E-05	1.04E+01	8.92E-02	1.18E-01	8.44E-02	1.86E+00	2.11E-02	6.55E-03	1.39E+00	1.53E-02
Trichloromethane {RoW}| market | Cut-off, U	1	kg	4.22E+00	3.39E+01	4.08E+00	8.96E-04	1.08E-01	4.09E-03	2.95E-03	4.29E-03	5.21E-03	6.17E-04	4.86E-05	6.85E+00	8.51E-02	1.13E-01	3.75E-01	4.91E+00	3.53E-02	6.29E-03	6.55E-01	2.27E-02
Ethanol, from ethylene {RoW}| market | Cut-off, U	1	kg	1.88E+00	5.31E+01	1.93E+00	4.68E-07	1.71E-02	5.22E-03	2.36E-03	5.65E-03	7.06E-03	1.04E-03	4.65E-05	4.22E+00	5.95E-02	7.95E-02	1.04E-01	1.61E+00	2.72E-02	5.29E-03	1.12E+00	6.03E-04

1-butanol {GLO}| market | Cut-off, U (Normal butanol)	1	kg	3.67E+00	9.33E+01	3.78E+00	9.37E-07	2.08E-01	9.14E-03	5.34E-03	9.85E-03	1.29E-02	1.38E-03	1.06E-04	7.16E+00	1.02E-01	1.36E-01	1.73E-01	2.74E+00	7.36E-02	7.49E-03	1.86E+00	1.18E-01
Nitric acid {CN}| market | Cut-off, U	1	kg	3.41E+00	1.36E+01	3.62E+00	7.73E-05	1.27E-02	3.00E-03	2.61E-03	3.17E-03	9.08E-03	3.55E-04	2.22E-05	4.52E+00	5.15E-02	6.79E-02	6.20E-02	1.08E+00	2.22E-02	4.20E-03	2.80E-01	1.70E-02
Natural gas, high pressure {CN}| market | Cut-off, U	1	m^3	3.71E-01	4.16E+01	4.09E-01	4.00E-08	2.19E-03	1.05E-03	1.83E-04	1.33E-03	4.08E-04	2.68E-05	2.34E-06	2.37E-01	3.36E-03	4.67E-03	2.81E-02	6.79E-02	7.29E-03	1.28E-03	9.10E-01	7.25E-04
Biomass fuel, see Table S5	1	kg	1.05E-01	1.33E+00	1.09E-01	2.19E-07	3.11E-03	3.30E-04	1.58E-04	3.36E-04	3.57E-04	2.03E-05	1.94E-06	2.38E-01	2.47E-03	3.30E-03	4.14E-03	8.56E-02	1.29E-01	3.83E-04	2.49E-02	5.14E-04
Base oil {GLO}| market | Cut-off, U (Conduction oil)	1	kg	1.61E+00	6.66E+01	1.68E+00	4.93E-07	9.70E-03	4.02E-03	2.35E-03	4.71E-03	6.74E-03	6.00E-05	9.77E-05	5.54E+00	8.53E-03	1.73E-02	3.74E-02	2.86E-01	2.64E-02	1.63E-03	1.45E+00	1.03E-02
Water, decarbonised {CN}| market | Cut-off, U	1	kg	1.34E-04	1.68E-03	1.39E-04	3.07E-11	5.14E-06	4.15E-07	2.10E-07	4.20E-07	4.66E-07	1.94E-07	2.04E-07	1.85E-04	3.12E-06	4.24E-06	3.83E-05	3.69E-04	3.13E-06	1.39E-07	3.14E-05	9.83E-04
Activated carbon, granular {GLO}| market | Cut-off, U	1	kg	3.33E+00	4.32E+01	3.40E+00	6.41E-07	1.22E-01	8.02E-03	6.09E-03	8.17E-03	1.60E-02	1.37E-03	9.01E-05	3.45E+00	5.49E-02	7.58E-02	1.23E-01	2.39E+00	4.21E-02	1.68E-03	8.54E-01	7.64E-03
Wastewater, average {RoW}| market | Cut-off, U	1	kg	2.72E-04	3.07E-03	2.86E-04	8.23E-10	1.06E-05	6.82E-07	4.26E-07	7.03E-07	8.32E-07	6.35E-06	2.26E-06	1.21E-03	3.91E-05	5.31E-05	4.92E-05	2.20E-03	5.75E-06	2.19E-06	5.79E-05	-1.90E-03
Average incineration residue, landfill {RoW}| market | Cut-off, U	1	kg	3.58E-01	2.45E+00	3.61E-01	3.05E-08	3.29E-03	8.92E-04	2.96E-04	9.14E-04	7.12E-04	3.18E-03	4.42E-06	6.01E-01	5.01E-01	6.88E-01	4.16E+00	1.07E+01	7.01E-03	1.33E-03	5.00E-02	1.14E-03
Inert waste, sanitary landfill {RoW}| transformation | Cut-off, U	1	kg	1.18E-02	2.74E-01	1.21E-02	3.74E-09	2.71E-04	8.32E-05	2.35E-05	8.67E-05	4.78E-05	3.55E-06	5.01E-07	3.62E-02	1.70E-02	2.39E-02	3.13E-03	8.69E-01	1.08E-03	3.91E-05	5.77E-03	2.62E-04
Municipal solid waste, sanitary landfill {RoW}| transformation | Cut-off, U	1	kg	6.11E-01	3.81E-01	7.46E-01	4.89E-08	1.08E-03	1.15E-04	5.09E-05	1.18E-04	1.08E-04	7.26E-04	8.23E-04	6.01E-02	4.32E-01	5.67E-01	1.62E-02	9.29E+00	1.21E-03	5.26E-05	7.52E-03	3.11E-04
Waste plastic, mixture, sanitary landfill | {RoW}| transformation Cut-off, U	1	kg	1.01E-01	2.84E-01	1.17E-01	8.14E-09	3.48E-04	8.61E-05	2.57E-05	8.96E-05	5.26E-05	1.58E-03	1.80E-03	3.86E-02	1.57E-01	2.11E-01	3.59E-03	4.11E+00	1.09E-03	4.02E-05	5.93E-03	2.66E-04

Notice: The impact categories are global warming potential based on GWP IPCC 100a (GWP 100, kg CO_2 eq), Cumulative energy demand (CED, MJ), global warming potential (GWP, kg CO_2 eq), stratospheric ozone depletion (ODP, kg CFC11 eq), ionizing radiation (IRP, kBq Co-60 eq), ozone formation-human health (OFHH, kg NO_x eq), fine particulate matter formation (PMFP, kg $PM_{2.5}$ eq), ozone formation-terrestrial ecosystems (OFTE, kg NOx eq), terrestrial acidification (TAP, kg SO_2 eq), freshwater eutrophication (FEP, kg P eq), marine eutrophication (MEP, kg N eq), terrestrial ecotoxicity (TEP, kg 1,4-DCB), freshwater ecotoxicity (FETP, kg 1,4-DCB), marine ecotoxicity (METP, kg 1,4-DCB), human carcinogenic toxicity (HTPc, kg 1,4-DCB), human noncarcinogenic toxicity (HTPcn, kg 1,4-DCB), land use potential (LUP, m^2a crop eq), mineral resource scarcity (SOP, kg Cu eq), fossil resource scarcity (FFP, kg oil eq), and water consumption (WCP, m^3).

References

1. Q. Deng, S. Z. You, W. X. Min, Y. K. Xu, W. Lin, J. Lu and C. H. Yang, *Adv. Mater.*, 2024, **36**, 10.
2. J. Y. Sun, Y. C. Li, L. Z. Lv, L. F. Wang, W. X. Xiong, L. Huang, Q. T. Qu, Y. Wang, M. Shen and H. H. Zheng, *Adv. Funct. Mater.*, 2024, **34**, 11.
3. Y. Y. Liu, J. J. Gu, J. L. Zhang, F. Yu, J. Wang, N. Nie and W. Li, *RSC Adv.*, 2015, **5**, 9745-9751.
4. F. F. Zhao, R. X. Tang, L. M. Yu, L. Ma and L. M. Wei, *J. Energy Storage*, 2024, **104**, 9.
5. T. Liu, T. T. Dong, M. Y. Wang, X. F. Du, Y. L. Sun, G. J. Xu, H. R. Zhang, S. M. Dong and G. L. Cui, *Nat. Sustain.*, 2024, **7**, 13.
6. L. Yang, S. N. Li, Y. M. Zhang, H. B. Feng, J. P. Li, X. Y. Zhang, H. Guan, L. Kong and Z. H. Chen, *J. Energy Chem.*, 2024, **97**, 30-45.
7. M. A. M. Hossain, M. A. Hannan, P. J. Ker, S. K. Tiong, M. A. Salam, M. Abdillah and T. M. I. Mahlia, *J. Energy Storage*, 2024, **99**, 35.
8. F. Piccinno, R. Hischier, S. Seeger and C. Som, *J. Clean Prod.*, 2016, **135**, 1085-1097.
9. S. K. Wang, Y. Zhang, H. R. Gao, K. D. Jin, C. Ao, L. N. Tian, Q. Y. He, B. J. Yi, P. Ai, W. Y. Cao, Y. Q. Pu, Y. J. Cheng and Q. Li, *Green Chem.*, 2025, **27**, 14.
10. LEA, International Energy Agency Home Page, https://www.iea.org/ (accessed Dec 10, 2024).
11. J. Moreno, J. Iglesias, J. Blanco, M. Montero, G. Morales and J. A. Melero, *J. Clean Prod.*, 2020, **250**, 119568.
12. Z. Wang, T. Lei, M. Yang, Z. Li, T. Qi, X. Xin, X. He, A. Ajayebi and X. Yan, *Applied Energy*, 2017, **192**, 83-94.
13. G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, *Int. J. Life Cycle Assess.*, 2016, **21**, 1218-1230.
14. Y. Cao, B. Zhang, X. Ou, Y. Li, C. Wang, L. Cao, C. Peng and J. Zhang, *New Journal of Chemistry*, 2019, **43**, 7386-7392.
15. M. U. Hameed, Y. khan, S. Ali, Z. Wu, S. U. Dar, H. Song, A. Ahmad and Y. Chen, *Ceramics International*, 2017, **43**, 741-748.
16. M. Usman Hameed, S. Ullah Dar, S. Ali, S. Liu, R. Akram, Z. Wu and I. S. Butler, *Physica E: Low-dimensional Systems and Nanostructures*, 2017, **91**, 119-127.
17. G. Bozkurt and E. Bozkurt, *Chemical Papers*, 2024, **78**, 4469-4480.
18. F. Zhao, R. Tang, L. Yu, L. Ma and L. Wei, *J. Energy Storage*, 2024, **104**, 114569.
19. C. Vidal-Abarca, P. Lavela and J. L. Tirado, *J. Power Sources*, 2011, **196**, 6978-6981.
20. R. B. Khomane, A. C. Agrawal, B. D. Kulkarni, S. Gopukumar and A. Sivashanmugam, *Materials Research Bulletin*, 2008, **43**, 2497-2503.

21. H.-Q. Wang, X.-H. Zhang, F.-H. Zheng, Y.-G. Huang and Q.-Y. Li, *Journal of Solid State Electrochemistry*, 2015, **19**, 187-194.
22. Q. Zhao, X. Li, Z. Shao, C. Liu and R. Zevenhoven, *Ionics*, 2019, **25**, 5565-5573.
23. Y. Hu, G. Wang, C. Liu, S.-L. Chou, M. Zhu, H. Jin, W. Li and Y. Li, *Ceramics International*, 2016, **42**, 11422-11428.
24. Y. Zhao, X. Cao, G. Fang, Y. Wang, H. Yang, S. Liang, A. Pan and G. Cao, *Chemical Engineering Journal*, 2018, **339**, 162-169.
25. L. Qu, M. Li, P. Liu, X. Tian, Y. Yi and B. Yang, *International Journal of Electrochemical Science*, 2018, **13**, 12311-12319.
26. L. Chladil, O. Čech, J. Smejkal and P. Vanýsek, *J. Energy Storage*, 2019, **21**, 295-300.
27. Q. Deng, S. You, W. Min, Y. Xu, W. Lin, J. Lu and C. Yang, *Adv. Mater.*, 2024, **36**, 2312924.
28. K. Huang, X. Zeng, D. Zhang, Y. Wang, M. Lan, C. Wen and Y. Guo, *Nano Res.*, 2024, **17**, 5243-5250.
29. M. Liang, H. Zhou, Q. Huang, S. Hu and W. Li, *Journal of Applied Electrochemistry*, 2011, **41**, 991-997.
30. M.-C. Huang, S.-H. Huang, S.-C. Chiu, K.-L. Hsueh, W.-S. Chang, C.-C. Yang, C.-C. Wu and J.-C. Lin, *Journal of the Chinese Chemical Society*, 2018, **65**, 1239-1244.
31. J. Li, Y. Huang, S. Zhang, W. Jia, X. Wang, Y. Guo, D. Jia and L. Wang, *ACS Appl. Mater. Interfaces*, 2017, **9**, 7499-7504.
32. J. Xu, Q. Duan, L. Zhang, Y. Liu, J. Sun and Q. Wang, *Journal of Loss Prevention in the Process Industries*, 2022, **77**, 104784.
33. L. Li, Y. zhang, Q. Li, W. Zhan, Z. Chen, M. Chen and Y. Cheng, *J. Energy Storage*, 2025, **114**, 115780.