Preliminary environmental impact assessment of PFOS waste treatment in a lab-scale batch subcritical water decomposition operation

Jianxin Zhu · Shaoguo Kang · Yijun Xie · Fushen Zhang

Received: 28 September 2012 / Accepted: 20 June 2013 / Published online: 13 July 2013
© Springer Japan 2013

Abstract Life cycle assessment (LCA) was carried out by SimaPro 7.3 to study the environmental impact of a lab-scale batch subcritical water decomposition operation for a kilogram of Perfluorooctane sulfonic acid (PFOS) waste treatment in this study, a proven process for the decomposition of PFOS pollutants with high concentration. This LCA focuses on not only the main environmental factors from emissions of toxic pollutants, but also the influence from technical characteristics of the iron-induced subcritical water technology including energy and substances consumption during the subcritical water decomposition treatment process. The IMPACT 2002+ environmental model was used to evaluate the 15 midpoint and 4 end-point environmental damages. It was found that the energy consumption to sustain the high temperature (350 °C) and high pressure (23 MPa) in the subcritical water process contributes 99.8 % of the damages. The total negative impact of the SCWD process for 1 kg of PFOS waste treatment to human health, ecological quality, climate change and resources amounts to 1.11×10^{-3} , 8.43×10^{-5} , 9.76×10^{-4} , 9.05×10^{-4} Pt, respectively. And the improvement of energy efficiency and catalytic effectiveness are two important factors to reduce the environmental impact from the SCWD process for the treatment of PFOS waste.

Keywords PFOS · Life cycle assessment · Subcritical water

Introduction

Perfluorooctane sulfonic acid (PFOS) has certain unique physiochemical properties, such as high surface-active effect, good light transparency, thermal and chemical stability, and has been worldwide used as industrial products or raw materials for surface treatment agents [1]. Although PFOS and its salts were categorized as persistent organic pollutants (POPs) at the 4th Conference of the Parties (COP4) to the Stockholm Convention in 2009, they are essential chemicals in the semiconductor industry with no cost-effective substitutes yet identified [2]. PFOS was the key ingredient of numerous stain and durable waster repellents applied to fabric, furniture and carpets [3, 4]. Together with perfluorooctanoic acid, it could be used for the production of fire-fighting and alcohol-type concentrate foams. Also, PFOS was widely used as photoacid generators and anti-reflective coatings in the semiconductor industries.

China is currently one of the few countries with increasing PFOS production and usage with an annual amount of about 200 tons, including: fabric processing 100 tons, metal plating 25 tons, semiconductor manufacturing 0.5 tons and fire-fighting foam 80 tons [5]. Recently, some research showed that PFOS contaminants could be detected in the water bodies, especially those near big cities, which mainly comes from industrial production and utilization [6, 7]. It was also found that the PFOS concentration in the water near the semiconductor manufacturing companies was much higher than the background level, which indicates the contribution of PFOS waste

Designation of the 7th International Conference on Waste Management and Technology, China, 2012

J. Zhu (✉) · S. Kang · Y. Xie · F. Zhang
Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences,
Beijing 100085, China
e-mail: zhujx@rcees.ac.cn

discharged from industries is not negligible in the environment [8]. The release control of PFOS, by-product, and residuals to air, water, and land is an effective means to alleviate the nearby PFOS contamination and the environmental sound treatment and safe disposal of PFOS pollutants is critical to effectively protect human health from those toxic chemicals.

The decomposition of PFOS is difficult because the cleavage of the C–F bonds to form fluorine ions (F^-) needs high energy input. The organic C–F bonds in PFOS yield a more stable molecular structure, such as the bond energy of C_2F_5-F of 127 kcal/mol vs. C_2H_5-H of 101 kcal/mol [9]. The oxidative-reductive electric position of F/F^- is as high as 3.6 V. Most conventional degradation technologies are ineffective for the in situ degradation of PFOS since they are inherently recalcitrant to chemical and microbiological treatment. They persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment. Although several technologies were proven to be effective in some degree for the treatment of PFOS waste, such as persulfate photolysis, direct UV photolysis, phosphotungstic acid photocatalysis, TiO_2 photocatalysis, $Fe(II)/Fe(III)$ photocatalysis, UV-KI photolysis, Alkaline 2-propanol photolytic reduction and B12 mediated reduction [10], there are still many unresolved issues with those processes and the more toxic and stable by-products make them difficult to meet the requirements of PFOS treatment in an environmentally sound way.

The subcritical water decomposition reported by Hori et al. [11] shows a promising feature for the final treatment of PFOS, since PFOS could be decomposed in a subcritical water reactor without any formation of perfluorocarboxylic acids. This method was also effective in decomposing other perfluoroalkylsulfonates bearing shorter chain (C-2–C-6) perfluoroalkyl groups and was successfully applied to the decomposition of PFOS contained in an antireflective coating agent used in semiconductor manufacturing. To achieve a complete decomposition of PFOS, high temperature, long reaction time and catalyst addition was required. The high energy and material consumption will inevitably produce some negative environmental impact in line with the environment benefits from the elimination of PFOS pollutants. It is necessary to assess the environmental impacts associated with all the stages of the subcritical water decomposition of PFOS in order to improve processes and provide a sound basis for informed decisions.

Life cycle assessment (LCA) is an internationally standardized methodology for systematic and quantitative evaluation of environmental impacts of functionally equivalent products or services through all stages of their life cycles, which was widely used in waste treatment and

groundwater remediation to evaluate the negative and positive impacts concerned [12, 13]. Related studies showed that LCA was an effective tool to identify environmental impacts and improve remediation technology in waste treatment and contaminated site remediation [14, 15]. This study presents a preliminary environmental impact assessment of PFOS waste treatment through LCA for a lab-scale batch subcritical water decomposing operation.

Process description

The process of PFOS decomposition in subcritical water was reported as a lab-scale batch operation [11]. The subcritical water reactor was a stainless steel high-pressure reactor equipped with a thermocouple. In a typical run, an argon-saturated aqueous mixture of PFOS waste and zerovalent iron metal powder was introduced into the reactor under an argon atmosphere, and the reactor was sealed. Then the reactor was heated to the desired reaction temperature, and the temperature was held constant for a specific time. After reaction, the reactor was cooled to room temperature and opened under an argon atmosphere, and the reaction mixture was centrifuged to separate the solution phase and the solid phase (metal powder). The solid phase could be put into a landfill and the F^- containing wastewater could be treated effectively by a normal industrialized wastewater treatment process.

The input data for the material consumption in the subcritical process was reported by Hori et al. while the energy consumption for heating was calculated by energy balance in a smaller cylindrical reactor subcritical water decomposition (SCWD) reactor ($\Phi 30 \times 60$ cm). When the concentration of PFOS is 93–372 mmol/L, reaction in subcritical water with iron powder addition at 350 °C for 6 h could reduce the PFOS below the detection limit of high-performance liquid chromatography (HPLC) with conductometric detection. As for the other processes, such as mixing, separating, landfilling and wastewater treatment, the data were mainly obtained from the Ecoinvent database [16].

The fine iron metal powder could be prepared through direct atomization, electrolysis and reduction processes. Electric iron powders have good reactivity and their particle sizes could be controlled during the electrolysis process. The basic process for electric iron powder preparation includes: raw material grinding, anode preparation, electrolysis, acquisition cathode deposition of metal powder, cleaning (washing), dehydration, drying, annealing, crushing, screening and packaging. Here the process of electrolytic iron powder from a caustic soda solution was referenced since the powder could be obtained directly

from the ore [17], in which soluble iron anodes were employed in a 50 % caustic solution at 100 °C. The brittle deposit prepared was suitable for crushing and very fine and dendritic powder was obtained.

Life cycle assessment

LCA (also known as life cycle analysis and cradle-to-grave analysis) is a technique to assess the impacts that a product or process makes on the environment throughout its life span. The procedures of LCA are part of the ISO 14000 environmental management standards, which is carried out in four distinct phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. In this study, we performed LCA of PFOS decomposition in subcritical water using a LCA software “SimaPro 7.3” developed by PRe Consultants and a life cycle impact assessment (LCIA) method “Impact 2002+” developed by Jolliet et al. [16].

Goal and scope definition

The goal of this life cycle assessment was to assess the environmental impacts of a lab scale SCWD technology for PFOS treatment and detect high environmental impact processes for the purpose of improving its environmental performance and reducing substances consumption. The functional unit was 1 kg of PFOS contaminated waste from 300 mmol/L to less than the detection limit of HPLC for compiling the life cycle inventory of SCWD. The system boundary of LCA included both the first-order and second-order impacts, covering all the direct emissions and disposal and resources required for upstream electricity generation and chemicals manufacture. Also, we define no timeframe for the LCA in order to capture both long-term and short-term impacts.

The life cycle stages for the SCWD system was grouped into four major subsystems: SUB1-Argon and fine iron powder preparation and transportation; SUB2-Heat supply in the SCWD reactor at 350 °C for 6 h; SUB3-H₂ and CHF₃ gas emission; SUB4-F[−] containing wastewater treatment and solid residual landfill. The basic structure of the lab-scale batch SCWD for PFOS treatment is presented in Fig. 1. Here, only operation phases were considered when analyzing technologies. Impacts associated with the process of production of capital goods were excluded from this study taking into account the lack of data for the SCWD infrastructures.

There are mainly three processes in SUB1: argon preparation, iron powder preparation and their transportation. As for the argon preparation, the Ecoinvent system process of “Argon, liquid at plant/RER S” was adopted, in

which the argon is produced by the fractional distillation of liquid air and hydrogen is used for the catalyst to burn oxygen impurities. Where, the “RER” means the data of the process are from Europe and the “S” at the end of the input name means that all processes to create the input are considered as a whole. The iron powder is prepared by an alkaline electrolysis process as referenced [17]. The process “Transport, van < 3.5t/RER S” in the Ecoinvent database was adopted for the transportation of argon and iron powder products, in which the operation of vehicle, production, maintenance and disposal of vehicles, construction and maintenance and disposal of roads were covered as unit processes.

Electricity was supposed to be used to heat the water at 350 °C for 6 h and the major process in SUB2 is the electricity generation and transformation. The Ecoinvent system process of “Electricity, oil, at power plant/UCTE S” was adopted in this study, in which the Union for the Coordination of the Transmission of Electricity (UCTE) specific efficiency of electricity generation and transformation was adopted. The electricity production in oil power plants with average efficiency and oil input in Europe was calculated in the process. The H₂ and CHF₃ emission resulting from the PFOS decomposition was covered in SUB3, which was supposed to emit into the ambient air without further treatment.

There are mainly three processes in SUB4: wastewater treatment, solid residual transportation and landfill. As for the wastewater treatment, the process of “Treatment, sewage, to wastewater treatment, class 2/CH S” in the Ecoinvent system was adopted, which belongs to a moderately large municipal wastewater treatment plant with a design capacity of about two million gallons per day (capacity class 2). Where, “CH” means the scenario was from Switzerland. Three stage wastewater treatments (mechanical, biological, chemical) including sludge digestion (fermentation) were used in the process according to the average technology in Switzerland. As for the landfill disposal, the scenario of inert material landfill specific to the technology encountered in Switzerland for inert waste with 5 % water was selected in the Ecoinvent system. In the process, no direct emissions from inert material landfill (leachate) are inventoried as deemed negligible. Module contains only exchanges to process-specific burdens (energy, land use) and infrastructure. The landfill was operated with renaturation after closure.

Life cycle inventory

In the inventory analysis phase, inputs (energy and chemicals used) and outputs (emissions to the environment) associated with the SCWD treatment processes should be analyzed in detail. And the major processes and their

Fig. 1 Major processes and system boundary of SCWD for PFOS decomposition in a lab-scale batch operation

Table 1 Major processes and their contributions in the PFOS waste treatment in a lab-scale batch SCWD operation

Process	Project	Unit	Total
Argon, liquid, at plant/RER S	Ecoinvent system processes	kg	8.92E−03
Disposal, inert waste, 5 % water, to inert material landfill/CH S	Ecoinvent system processes	kg	5.36E−02
Electricity, oil, at power plant/UCTE S	Ecoinvent system processes	MJ	1.99E+01
Iron ore, 65 % Fe, at beneficiation/GLO S	Ecoinvent system processes	kg	8.68E−05
Sodium hydroxide (concentrated) E	Industry data 2.0	kg	1.12E−04
Transport, van < 3.5t/RER S	Ecoinvent system processes	tkm	1.80E−04
Treatment, sewage, to wastewater treatment, class 2/CH S	Ecoinvent system processes	m ³	1.00E−03
Water, decarbonised, at plant/RER S	Ecoinvent system processes	kg	2.23E−04

“CH” means the scenario is from Switzerland; “RER” and “E” mean the data are from Europe; “GLO” means the scenarios belong to a global average level; “UCTE” means the data are from the Union for the Co-ordination of Transmission of Electricity; and the “S” at the end of the input name means that all processes to create the input are considered as a whole

contributions in the PFOS waste treatment are listed in Table 1. The foreground life cycle inventory (LCI) data for PFOS decomposition in the SCWD system and fine iron powder through electrolysis were compiled directly from the related papers published [11, 17]. The background life cycle inventory data (e.g., life cycle inventory of 1 kWh electricity, 1 kg of fuel oil, 1 kg of activated carbon) were provided by the Ecoinvent Database based on average technology data, as implemented in SimaPro 7.3. Table 2 lists the major substances used in the life cycle inventory for 1 kg of PFOS waste treatment in a lab-scale batch SCWD operation.

Life cycle impact assessment

The LCIA methodology adopted for this study was IMPACT 2002+, as implemented in SimaPro 7.3. This methodology proposes a feasible implementation of a

combined midpoint and end-point approach by linking all types of LCI results via 15 midpoint impacts to 4 end-point damages [16]. Figure 2 shows the overall scheme of the IMPACT 2002+ framework, where the solid arrows symbolize that relevant impact pathways are known or assumed to exist and the dotted arrows indicate that these uncertain impact pathways between midpoint and end-point levels are not modelled quantitatively. All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. These four damage categories are expressed respectively in disability-adjusted life years (DALY), potentially disappeared fraction of species over a square meter during a year (PDF m² year), kilogram equivalent of carbon dioxide (kg CO_{2-eq}), and mega Joules (MJ).

Table 3 lists the midpoint impacts of the SCWD in a lab-scale batch operation and the contribution distribution

Table 2 Major substances used in the life cycle inventory for 1 kg PFOS waste treatment in a lab-scale batch SCWD operation

No	Substance	Compartment	Unit	SUB1-Ar and iron powder preparation	SUB2-heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ waste water treatment
1	Heat, waste	Air	MJ	6.21E-02	3.11E+01	×	1.13E-02
2	Carbon dioxide, fossil	Air	kg	3.51E-03	4.75E+00	×	6.51E-04
3	Sulfur dioxide	Air	kg	1.41E-05	3.64E-02	×	1.89E-06
4	Nitrogen oxides	Air	kg	8.13E-06	1.52E-02	×	4.69E-06
5	Argon	Air	kg	×	×	8.92E-03	×
6	Carbon dioxide, biogenic	Air	kg	7.99E-05	4.33E-03	×	2.22E-04
7	Methane, fossil	Air	kg	5.83E-06	2.65E-03	×	1.48E-06
8	Carbon monoxide, fossil	Air	kg	3.52E-06	1.69E-03	×	2.03E-06
9	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	1.02E-06	1.49E-03	×	9.23E-07
10	Particulates, < 2.5 µm	Air	kg	9.22E-07	6.97E-04	×	3.60E-07
11	Particulates, > 10 µm	Air	kg	2.08E-06	5.99E-04	×	3.63E-07
12	Particulates, > 2.5 µm, and < 10 µm	Air	kg	4.64E-07	4.26E-04	×	2.27E-07
13	Dinitrogen monoxide	Air	kg	1.21E-07	2.38E-04	×	1.17E-07
14	Carbon dioxide	Air	kg	1.25E-04	×	×	×
15	Pentane	Air	kg	3.63E-08	1.01E-04	×	1.69E-08
16	Propane	Air	kg	3.84E-08	8.58E-05	×	1.37E-08
17	Oil, crude, in ground	Raw	kg	3.51E-04	1.39E+00	×	2.22E-04
18	Water, turbine use, unspecified natural origin	Raw	m ³	2.10E-02	9.15E-01	×	3.24E-03
19	Water, cooling, unspecified natural origin/m ³	Raw	m ³	1.70E-04	5.54E-01	×	5.01E-06
20	Energy, potential (in hydropower reservoir), converted	Raw	MJ	2.61E-03	1.12E-01	×	4.69E-04
21	Calcite, in ground	Raw	kg	4.87E-05	8.48E-02	×	1.47E-04
22	Gas, natural, in ground	Raw	m ³	2.99E-04	7.40E-02	×	4.23E-05
23	Gravel, in ground	Raw	kg	2.46E-04	6.14E-02	×	6.94E-03
24	Coal, brown, in ground	Raw	kg	1.01E-03	4.17E-02	×	2.91E-05
25	Energy, gross calorific value, in biomass	Raw	MJ	7.59E-04	3.57E-02	×	5.22E-05
26	Coal, hard, unspecified, in ground	Raw	kg	5.65E-04	3.32E-02	×	5.22E-05
27	Energy, kinetic (in wind), converted	Raw	MJ	4.17E-04	1.71E-02	×	1.19E-05
28	Iron, 46 % in ore, 25 % in crude ore, in ground	Raw	kg	8.10E-05	1.30E-02	×	3.28E-05
29	Barite, 15 % in crude ore, in ground	Raw	kg	1.79E-06	7.07E-03	×	6.58E-07
30	Water, river	Raw	m ³	1.89E-05	4.96E-03	×	3.70E-06
31	Occupation, industrial area	Raw	m ² a	2.82E-06	4.61E-03	×	5.77E-07
32	Carbon dioxide, in air	Raw	kg	8.48E-05	3.88E-03	×	5.32E-06
33	Water, unspecified natural origin/m ³	Raw	m ³	1.83E-06	3.60E-03	×	1.07E-05
34	Clay, unspecified, in ground	Raw	kg	4.91E-06	3.17E-03	×	5.23E-05
35	Occupation, forest, intensive, normal	Raw	m ² a	3.70E-05	2.48E-03	×	5.28E-06
36	Volume occupied, reservoir	Raw	m ³ y	4.82E-05	2.00E-03	×	8.81E-06

Table 2 continued

No	Substance	Compartment	Unit	SUB1-Ar and iron powder preparation	SUB2-heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ waste water treatment
37	Transformation, from forest	Raw	m ²	4.53E-07	1.79E-03	×	1.66E-07
38	Transformation, to mineral extraction site	Raw	m ²	4.75E-07	1.71E-03	×	3.55E-07
39	Water, salt, sole	Raw	m ³	2.46E-07	1.10E-03	×	1.21E-07
40	Occupation, traffic area, road network	Raw	m ² a	7.87E-06	1.01E-03	×	2.50E-05
41	Energy, from gas, natural	Raw	MJ	1.00E-03	×	×	×
42	Sodium chloride, in ground	Raw	kg	1.16E-04	8.64E-04	×	1.03E-05
43	Water, cooling, unspecified natural origin/kg	Raw	kg	7.37E-04	×	×	×
44	Energy, from uranium	Raw	MJ	6.12E-04	×	×	×
45	Clay, bentonite, in ground	Raw	kg	4.55E-07	5.55E-04	×	4.55E-07
46	Water, salt, ocean	Raw	m ³	2.90E-06	5.44E-04	×	1.95E-07
47	Transformation, from sea and ocean	Raw	m ²	1.58E-07	5.21E-04	×	3.55E-08
48	Transformation, to dump site, benthos	Raw	m ²	1.57E-07	5.21E-04	×	3.54E-08
49	Occupation, dump site, benthos	Raw	m ² a	1.57E-07	5.21E-04	×	3.54E-08
50	Occupation, water bodies, artificial	Raw	m ² a	5.01E-06	4.28E-04	×	7.72E-07
51	Energy, from coal	Raw	MJ	4.33E-04	×	×	×
52	Occupation, water courses, artificial	Raw	m ² a	2.27E-06	4.15E-04	×	4.67E-07
53	Occupation, mineral extraction site	Raw	m ² a	2.41E-06	4.04E-04	×	2.12E-06
54	Water, process, unspecified natural origin/kg	Raw	kg	3.33E-04	×	×	×
55	Gas, mine, off-gas, process, coal mining/m ³	Raw	m ³	5.48E-06	3.24E-04	×	5.31E-07
56	Water, well, in ground	Raw	m ³	4.20E-06	2.79E-04	×	1.60E-06
57	Occupation, dump site	Raw	m ² a	3.38E-06	2.28E-04	×	2.47E-05
58	Energy, from oil	Raw	MJ	2.54E-04	×	×	×
59	Energy, solar, converted	Raw	MJ	6.00E-06	2.47E-04	×	4.34E-07
60	Nickel, 1.98 % in silicates, 1.04 % in crude ore, in ground	Raw	kg	6.92E-07	2.13E-04	×	2.85E-06
61	Magnesite, 60 % in crude ore, in ground	Raw	kg	1.82E-07	1.72E-04	×	5.22E-07
62	Occupation, construction site	Raw	m ² a	1.09E-07	1.63E-04	×	2.60E-06
63	Occupation, industrial area, built up	Raw	m ² a	2.38E-07	1.52E-04	×	2.25E-06
64	Energy, from hydro power	Raw	MJ	1.12E-04	×	×	×
65	Fluorspar, 92 %, in ground	Raw	kg	8.91E-08	1.11E-04	×	3.34E-08
66	Energy, gross calorific value, in biomass, primary forest	Raw	MJ	3.74E-08	9.14E-05	×	2.01E-08
67	Occupation, industrial area, vegetation	Raw	m ² a	1.62E-07	8.42E-05	×	2.20E-06

Table 2 continued

No	Substance	Compartment	Unit	SUB1-Ar and iron powder preparation	SUB2-heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ waste water treatment
68	Transformation, to heterogeneous, agricultural	Raw	m ²	2.11E-08	8.34E-05	×	9.65E-09
69	Heat, waste	Soil	MJ	1.18E-04	1.10E-02	×	6.80E-05
70	Oils, unspecified	Soil	kg	1.34E-06	6.40E-03	×	3.98E-07
71	Calcium	Soil	kg	6.44E-08	1.66E-04	×	1.94E-06
72	Chloride	Soil	kg	1.77E-06	1.57E-04	×	2.75E-07
73	Carbon	Soil	kg	3.19E-08	1.24E-04	×	6.70E-06
74	Iron	Soil	kg	3.99E-08	8.93E-05	×	5.15E-06
75	Sodium	Soil	kg	2.49E-08	8.25E-05	×	8.50E-09
76	Heat, waste	Water	MJ	5.14E-03	1.30E+01	×	1.57E-03
77	Chloride	Water	kg	2.61E-05	4.66E-02	×	4.74E-05
78	Sodium, ion	Water	kg	3.45E-05	2.82E-02	×	7.53E-06
79	Sulfate	Water	kg	2.12E-04	2.01E-02	×	1.60E-04
80	COD, chemical oxygen demand	Water	kg	4.35E-06	1.96E-02	×	3.27E-05
81	BOD5, biological oxygen demand	Water	kg	4.16E-06	1.94E-02	×	1.16E-05
82	Calcium, ion	Water	kg	5.31E-05	6.39E-03	×	8.54E-05
83	Oils, unspecified	Water	kg	1.28E-06	6.06E-03	×	4.29E-07
84	TOC, total organic carbon	Water	kg	1.35E-06	5.98E-03	×	8.18E-06
85	DOC, dissolved organic carbon	Water	kg	1.34E-06	5.92E-03	×	8.42E-06
86	Silicon	Water	kg	3.91E-05	2.08E-03	×	6.01E-06
87	Magnesium	Water	kg	2.57E-05	1.65E-03	×	6.89E-06
88	Suspended solids, unspecified	Water	kg	8.27E-07	1.32E-03	×	1.12E-07
89	Potassium, ion	Water	kg	1.49E-05	1.08E-03	×	1.25E-06
90	Nitrogen	Water	kg	6.85E-08	4.17E-04	×	4.91E-07
91	Phosphate	Water	kg	8.45E-06	3.93E-04	×	3.28E-06
92	Iron, ion	Water	kg	7.34E-06	3.77E-04	×	8.05E-06
93	Carboxylic acids, unspecified	Water	kg	8.60E-08	3.85E-04	×	4.31E-08
94	Aluminium	Water	kg	4.60E-06	3.44E-04	×	3.64E-06
95	Barite	Water	kg	9.81E-08	3.24E-04	×	2.21E-08
96	Strontium	Water	kg	9.10E-07	2.00E-04	×	5.96E-08
97	Nitrate	Water	kg	2.53E-06	1.21E-04	×	4.85E-05
98	Solids, inorganic	Water	kg	3.57E-06	1.60E-04	×	1.27E-07
99	Manganese	Water	kg	1.99E-06	9.85E-05	×	1.93E-07
100	Sulfite	Water	kg	1.51E-08	9.12E-05	×	1.49E-10

of SUB1, SUB2, SUB3 and SUB4 for 1 kg PFOS waste treatment. It could be found that more than 97 % of the midpoint environmental impacts were contributed by SUB2-Heat supply to sustain the high temperature of 350 °C and the high pressure of 23 MPa in the SCWD reactor. The other subsystems SUB1-Ar and iron powder preparation and SUB4-F⁻ wastewater treatment only contribute less than 3 % of the midpoint impacts. As for

SUB3-CHF₃ and H₂ emission, it contributes only 0.3 % on the global warming impact from its greenhouse gas emission. The major sources of midpoint impacts from SUB2 were specially analyzed in the following.

Human toxicity (carcinogenic and non-carcinogenic effects) represents all effects on human health in IMPACT2002+, in which the cumulative toxicological risk and potential impacts associated with a specified mass

Fig. 2 Overall scheme of the IMPACT 2002+ framework (Full arrows symbolize that a relevant impact pathway is known and quantitatively modeled. Dotted arrows represent impact pathways that are assumed to exist, but that are not modeled.)

(kg) of a chemical emitted into the environment are determined by the chemical toxic model [18]. The reference substance is chloroethylene (C_2H_3Cl) emitted into air for the midpoint characterization factors (CFs) of human toxicity and the CFs are expressed in kilogram equivalent of chloroethylene into air ($kg\ C_2H_3Cl_{eq}$). The electric power consumption is about 0.4542 kWh to heat 1 kg PFOS containing waste from 20 °C at 1 atm pressure to 350 °C at 23.3 MPa in SUB2. When a smaller cylindrical reactor SCWD reactor ($\Phi\ 30 \times 60\ cm$) is supposed to be used in the operation, the heat consumption to hold the high temperature for 6 h in a batch operation is about 5.5135 kWh. The carcinogenic effects of aromatic hydrocarbons discharged to water and emitted into air, dioxins and arsenic emitted into air compartment from fossil fuel burning for electricity generation are as high as 4.80×10^{-3} , 4.42×10^{-3} , 1.17×10^{-3} and $5.70 \times 10^{-4}\ kg\ C_2H_3Cl_{eq}$, as shown in Table 4, respectively. They account for more than 90.3 % of the total carcinogenic damage effects. The major non-carcinogenic substances considered in SUB2 are dioxins and arsenic emitted into the air, barium discharged to water, and arsenic released to soil, their non-carcinogenic contributions are about 5.92×10^{-3} , 5.72×10^{-3} , 2.56×10^{-3} and $1.68 \times 10^{-3}\ kg\ C_2H_3Cl_{eq}$, as shown in Table 5,

respectively. They take more than 76.6 % of the whole non-carcinogenic damage effects.

Respiratory effects caused by inorganics were expressed in kilogram equivalents of $PM_{2.5}$ into air ($kg\ PM_{2.5}\ into\ air_{eq}$) and obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance [19]. The air emissions of sulfur dioxide, nitrogen oxides and $PM_{2.5}$ from the electricity generation in SUB2 are about 2.84×10^{-3} , 1.93×10^{-3} and $6.97 \times 10^{-4}\ kg\ PM_{2.5_{eq}}$, which account for about 99.8 % of the total respiratory effects caused by inorganics. Both the CFs of human toxicity and respiratory effects could be normalized to the disability-adjusted life years through suitable normalization factors to make them comparable [20].

Terrestrial ecotoxicity effects were determined by dividing the damage CF of the reference substance triethylene glycol into soil ($kg\ TEG\ soil$) in the IMPACT 2002+ model [19]. It has been estimated that the substances have ecotoxic effects only by exposure through the aqueous phase in soil. The terrestrial ecotoxicity damage from SUB2 was about 0.431 $kg\ TEG\ soil$ or 46.2 $PDF\ m^2$ per year after normalization.

Global warming effects were expressed in kilogram equivalents of carbon dioxide into the air ($kg\ CO_{2_{eq}}\ into$

Table 3 Midpoint impacts of SCWD for 1 kg PFOS waste treatment in a lab-scale batch operation

Impact category	Unit	SUB1-Ar and iron powder preparation	%	SUB2-heat supply	%	SUB3-CHF ₃ emission	%	SUB4-F ⁻ wastewater treatment	%
Carcinogens	DALY	4.58E-11	0.13	3.39E-08	99.72	–	–	5.07E-11	0.15
Non-carcinogens	DALY	6.67E-11	0.11	5.78E-08	99.07	–	–	4.76E-10	0.82
Respiratory inorganics	DALY	2.17E-09	0.06	3.83E-06	99.92	–	–	8.05E-10	0.02
Ionizing radiation	DALY	4.94E-11	2.36	2.04E-09	97.39	–	–	5.16E-12	0.25
Ozone layer depletion	DALY	2.63E-13	0.04	6.10E-10	99.93	–	–	1.54E-13	0.03
Respiratory organics	DALY	1.61E-12	0.07	2.38E-09	99.88	–	–	1.26E-12	0.05
Aquatic ecotoxicity	PDF m ² year	9.31E-06	0.09	9.78E-03	98.49	–	–	1.41E-04	1.42
Terrestrial ecotoxicity	PDF m ² year	3.30E-04	0.08	4.31E-01	98.64	–	–	5.61E-03	1.28
Terrestrial acid/neutralization	PDF m ² year	6.18E-05	0.05	1.25E-01	99.92	–	–	3.46E-05	0.03
Land occupation	PDF m ² year	1.54E-05	0.28	5.37E-03	99.23	–	–	2.63E-05	0.49
Global warming	kg CO ₂ -eq	3.74E-03	0.08	4.81E+00	99.60	1.47E-02	0.30	6.93E-04	0.01
Non-renewable energy	MJ primary	7.40E-02	0.11	6.87E+01	99.87	–	–	1.56E-02	0.02
Mineral extraction	MJ primary	1.90E-05	0.41	4.53E-03	98.46	–	–	5.18E-05	1.13

“DALY” (“Disability-Adjusted Life Years”) characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital); “PDF m² year” (“Potentially Disappeared Fraction of species over a certain amount of m² during a certain amount of the year”) is the unit to measure the impacts on ecosystems; MJ (“Mega Joules”) measures the amount of energy extracted or needed to extract the resource

air) and taken from the IPCC list (IPCC 2001, and IPCC 2007 for CH₄, N₂O and CO). The Global Warming Potentials (GWPs) for a 100-year time horizon are used [21]. The major global warming substances considered in SUB2 are carbon dioxide, dinitrogen monoxide, methane, carbon monoxide, sulfur hexafluoride, methane, and ethane. The carbon dioxide emission from the oil burning for electric generation was about 4.81 kg for the treatment of 1 kg of PFOS waste, which takes more than 99 % of the whole contributions in SUB2, as shown in Table 6. And the contribution of CHF₃ emission in SUB3 is only 0.0147 kg CO₂-eq.

Non-renewable energy consumption effects, in terms of the total primary energy extracted, were expressed in mega Joules of total primary non-renewable energy/unit extracted and taken from the Ecoinvent system. The non-renewable energy consumption in SUB2 was mainly from the crude oil and natural gas usage, which accounts to 63.7 and 2.98 MJ for the treatment of 1 kg of PFOS waste, respectively.

Mineral extraction effects were expressed in mega Joules of surplus energy per kilogram extracted and taken directly from Eco-indicator 99 [16]. Surplus energy expresses the expected increase of extraction energy

needed to extract 5 times the cumulative extracted amount since the beginning of extraction until 1990. The total mineral extraction damage in SUB2 is about 0.0046 MJ surplus.

The normalization was performed in Impact 2002+ by dividing the impact (at damage categories) by the respective normalization factors. The unit of “point (pt)” is equal to “person year” in the SimaPro, which was used to express the respective share of each impact normalized to the overall damage of the considered category. The normalization factors for the four damage categories are 0.0071 DALY/point for human health, 13,800 PDF m² year/point for ecosystem quality, 11,600 kg CO₂ into air/point for climate change and 152,000 MJ/point for resources. A “pt” represents the average impact in a specific category caused by a person during one year in Europe. For human health, it also represents the average impact on a person during one year. It is calculated as the total yearly damage score due to emissions and extractions in Europe divided by the total European population.

More details could be found from the normalized midpoint scores of subsystems in Fig. 3. It could be found that most of the negative impacts are related to global warming, non-renewable energy, respiratory inorganics, and

Table 4 The carcinogenic substance emissions from 1 kg PFOS waste treatment by SCWD in a lab-scale batch operation (Unit: kg C₂H₃Cl_{eq})

No	Substances	Compartment	Total	SUB1-Ar & iron powder preparation	SUB2-heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ wastewater treatment
1	Hydrocarbons, aromatic	Air	4.44E-03	1.02E-05	4.42E-03	×	8.84E-06
2	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	1.18E-03	6.74E-07	1.17E-03	×	2.91E-06
3	Arsenic	Air	5.71E-04	6.06E-07	5.70E-04	×	1.78E-07
4	PAH, polycyclic aromatic hydrocarbons	Air	5.38E-04	7.52E-07	5.36E-04	×	7.08E-07
5	Benzo(a)pyrene	Air	1.17E-04	1.69E-06	1.15E-04	×	1.44E-07
6	Chromium	Air	1.10E-04	1.31E-07	1.09E-04	×	4.83E-07
7	Formaldehyde	Air	3.72E-05	3.30E-08	3.72E-05	×	5.13E-09
8	Cadmium	Air	8.72E-06	3.90E-09	8.71E-06	×	1.44E-09
9	Chromium VI	Air	2.66E-06	6.32E-09	2.64E-06	×	1.23E-08
10	Acetaldehyde	Air	9.10E-07	1.18E-09	9.08E-07	×	2.01E-10
11	Phenol, pentachloro-	Air	1.11E-07	2.63E-09	1.09E-07	×	8.12E-11
12	Beryllium	Air	7.78E-08	1.21E-10	7.77E-08	×	2.47E-11
13	Arsenic	Soil	1.65E-04	6.31E-08	1.61E-04	×	3.11E-06
14	Hydrocarbons, aromatic	Water	4.80E-03	1.12E-06	4.80E-03	×	7.28E-07
15	Arsenic, ion	Water	1.29E-04	1.02E-06	1.27E-04	×	9.83E-07
16	PAH, polycyclic aromatic hydrocarbons	Water	4.37E-05	1.08E-08	4.37E-05	×	6.94E-09
17	Toluene	Water	4.60E-07	1.08E-10	4.60E-07	×	7.19E-11
18	Benzene	Water	4.44E-07	1.12E-10	4.44E-07	×	1.17E-10
19	Methane, dichloro-, HCC-30	Water	2.09E-07	5.14E-11	2.09E-07	×	1.92E-11
20	Benzene, ethyl-	Water	5.96E-08	1.39E-11	5.96E-08	×	8.99E-12

terrestrial ecotoxicity. The human health impact from carcinogens and non-carcinogens pollutant emission and terrestrial acid and neutralization should also be considered. Nearly all of those environmental impacts arose from the fuel burning to supply enough heat in SUB2 to sustain a subcritical condition at high temperature and high pressure. Other impacts such as ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, land occupation and mineral extraction are three orders of magnitude lower than the global warming effect.

The midpoint impact categories can also be grouped into four end-point categories. Those four end-point categories were also calculated by respective damage factors and shown in Fig. 4. We can also compare the different end-point environmental damages between different subsystems. These results were normalized by comparing them against the environmental profile of an “average European”, which is embedded in the IMPACT 2002+ LCIA methodology in SimaPro 7.3. The results of end-point damage were also shown in the dimensionless unit “pt”, together with a summed total score. It could be found that the impacts to human health, climate change and resources are the major environmental impacts from the SCWD of

PFOS waste. The ecological quality impact is one order of magnitude lower than the climate change impact.

Life cycle impact assessment interpretation

To interpret the environmental impacts precisely, we calculated the endpoint impacts of the four subsystems of SCWD technology. The total negative impact to the human health, ecological quality, climate change and resources accounts to 1.11×10^{-3} , 8.43×10^{-5} , 9.76×10^{-4} , 9.05×10^{-4} Pt for a kg of PFOS waste, respectively. It could be found that most of the endpoint impacts were also generated by SUB2. That just shows the characteristics of a large amount fuel consumption in a subcritical water treatment process.

Figure 5 shows the process specific environmental impact of the SCWD system for PFOS waste treatment. It could be found that the SUB2-heat supply for the SCWD system contributes nearly all of the environmental impacts (99.8 %). Also, the argon consumption was also the major source of the environmental impact in a lab-scale batch subcritical water decomposition operation for the treatment of PFOS waste. When compared with other industrialized

Table 5 The non-carcinogenic substance emissions from 1 kg PFOS waste treatment by SCWD in a lab-scale batch operation (Unit: kg C₂H₃Cl_{-eq})

No	Substances	Compartment	Total	SUB1-Ar and iron powder preparation	SUB2-Heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ wastewater treatment
1	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	5.94E-03	3.40E-06	5.92E-03	×	1.47E-05
2	Arsenic	Air	5.73E-03	6.08E-06	5.72E-03	×	1.78E-06
3	Molybdenum	Air	8.16E-04	2.75E-07	8.16E-04	×	1.86E-08
4	Zinc	Air	1.71E-04	1.84E-07	1.70E-04	×	1.18E-07
5	Nickel	Air	1.58E-04	3.29E-08	1.58E-04	×	3.55E-09
6	Formaldehyde	Air	1.34E-04	1.19E-07	1.34E-04	×	1.85E-08
7	Cadmium	Air	1.34E-04	6.00E-08	1.34E-04	×	2.21E-08
8	Benzene	Air	8.69E-05	1.13E-07	8.68E-05	×	1.85E-08
9	Selenium	Air	6.13E-05	5.26E-08	6.12E-05	×	3.91E-09
10	Chromium	Air	1.62E-05	1.93E-08	1.61E-05	×	7.13E-08
11	Mercury	Air	1.44E-05	4.68E-08	1.44E-05	×	2.21E-08
12	Arsenic	Soil	1.71E-03	6.56E-07	1.68E-03	×	3.23E-05
13	Barium	Soil	1.05E-03	2.58E-07	1.05E-03	×	9.65E-08
14	Zinc	Soil	6.13E-04	7.40E-07	5.22E-04	×	9.03E-05
15	Aluminium	Soil	1.57E-04	5.42E-08	1.52E-04	×	5.53E-06
16	Molybdenum	Soil	1.23E-05	1.98E-08	8.95E-07	×	1.14E-05
17	Barium	Water	2.56E-03	6.01E-07	2.56E-03	×	3.87E-07
18	Arsenic, ion	Water	1.34E-03	1.07E-05	1.32E-03	×	1.02E-05
19	Cadmium, ion	Water	1.86E-05	1.38E-08	1.85E-05	×	1.13E-07
20	Nickel, ion	Water	1.07E-05	4.08E-09	1.07E-05	×	4.50E-08

waste treatment facilities, such as the high temperature incineration and base catalyzed decomposition for POPs waste disposal with environmental impacts of 0.279 and 0.147 Pt/ton PCBs waste, this lab scale SCWD reactor consumed too much energy to sustain the subcritical condition (350 °C and 23 MPa) for the PFOS waste disposal, which contributes the major negative environmental impacts in the operation [22, 23].

To improve the energy efficiency is one of the most important factors to reduce the environmental impact when sustaining the high temperature and high pressure from the SCWD process, such as heat recovery or using clean energy sources. When compared with the batch operation, the continuous operation could also improve the energy efficiency and reduce the heat loss in the SCWD operation. The improvement of catalyst is also necessary to shorten the reaction time and increase the system effectiveness for the PFOS waste treatment through the SCWD technology.

Uncertainty analysis

Uncertainties can occur in the inventory and impact assessment calculation in this study. For instance, the

inventory for both SCWD and the electric iron powder process was mainly from the published papers, unpublished data might have some impacts on the LCA of the whole process. Also, the inventories for some basic processes supplied by the Ecoinvent Database and adopted by this study have some uncertainties. There are also some uncertainties in the impact analysis approached in the IMPACT2002+ [16]. Generally speaking, uncertainties in inventory are high compared to uncertainties in impact analysis, when considering that most of the technological parameters were taken from a lab-scale batch SCWD operation. A detailed quantitative uncertainty analysis was not covered in this preliminary LCA study, which was supposed to be more meaningful for the improved and commercialized SCWD operation.

Conclusions

The IMPACT 2002+ environmental model was used to evaluate the environmental impact of a lab-scale batch subcritical water decomposition operation for a kg of PFOS waste treatment in this study. The total negative impacts of the SCWD process to the human health, ecological quality,

Table 6 The global warming substance emissions from 1 kg PFOS waste treatment by SCWD in a lab-scale batch operation (Unit kg CO₂-eq)

No	Substances	Compartment	Total	SUB1-Ar and iron powder preparation	SUB2-Heat supply	SUB3-CHF ₃ emission	SUB4-F ⁻ wastewater treatment
1	Carbon dioxide, fossil	Air	4.75E+00	3.51E-03	4.75E+00	×	6.51E-04
2	Dinitrogen monoxide	Air	3.71E-02	1.88E-05	3.71E-02	×	1.82E-05
3	Methane, fossil	Air	2.75E-02	6.03E-05	2.74E-02	×	1.53E-05
4	Methane, trifluoro-, HFC-23	Air	1.47E-02	1.65E-10	1.17E-08	1.47E-02	8.92E-11
5	Carbon monoxide, fossil	Air	2.66E-03	5.53E-06	2.65E-03	×	3.19E-06
6	Sulfur hexafluoride	Air	5.19E-04	1.23E-05	5.07E-04	×	5.92E-07
7	Methane, bromotrifluoro-, Halon 1301	Air	1.29E-04	3.21E-08	1.29E-04	×	2.73E-08
8	Carbon dioxide	Air	1.25E-04	1.25E-04	×	×	×
9	Methane, tetrafluoro-, CFC-14	Air	1.03E-04	1.30E-06	1.01E-04	×	4.41E-07
10	Methane, biogenic	Air	4.95E-05	9.88E-07	4.47E-05	×	3.89E-06
11	Ethane, hexafluoro-, HFC-116	Air	2.36E-05	2.96E-07	2.32E-05	×	1.04E-07
12	Carbon dioxide, land transformation	Air	2.11E-05	2.04E-07	2.09E-05	×	8.61E-09
13	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	1.09E-05	2.56E-07	1.06E-05	×	3.36E-08
14	Methane	Air	9.92E-06	9.92E-06	×	×	×
15	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	6.08E-06	7.03E-09	5.94E-06	×	1.30E-07
16	Methane, chlorodifluoro-, HCFC-22	Air	2.04E-06	3.38E-08	2.00E-06	×	1.84E-09
17	Methane, tetrachloro, CFC-10	Air	4.12E-07	4.95E-10	3.99E-07	×	1.30E-08
18	Methane, bromochlorodifluoro, Halon 1211	Air	3.72E-07	4.95E-09	3.67E-07	×	3.09E-10
19	Carbon monoxide	Air	1.59E-07	1.59E-07	×	×	×
20	Methane, dichlorodifluoro, CFC-12	Air	5.51E-08	4.18E-10	5.46E-08	×	7.76E-11

Fig. 3 Normalized midpoint impacts of SCWD for 1 kg of PFOS waste treatment in a lab-scale batch operation

climate change and resources are about 1.11×10^{-3} , 8.43×10^{-5} , 9.76×10^{-4} , 9.05×10^{-4} Pt per kg of PFOS waste, respectively. It was found that the energy consumption to sustain the high temperature and high pressure

in the subcritical water process contributes the most part of the environmental impact. And the improvement of energy efficiency and catalytic effectiveness is a potential way to reduce the environmental impacts from the SCWD process.

Fig. 4 Comparison of normalized endpoint scores of subsystems of the SCWD for 1 kg of PFOS waste treatment in a lab-scale batch operation

Fig. 5 Process environmental impact of the SCWD for 1 kg of PFOS waste treatment in a lab-scale batch operation

The LCA analysis was entirely based on European conditions and adopted without change for this study, so the conclusions are also strictly limited to this context, which may result in uncertainties because of data availability, system boundaries and the choice of impact analysis method.

Acknowledgments Support for this research was provided by the National Science Foundation of China (20977105 and 50708110) and the Environmental Public Welfare Project (201009026) and is gratefully acknowledged. We also want to thank PRé Consultants for providing the LCA software SIMARPO for this study.

References

1. Renner R (2008) PFOS phaseout pays off. *Environ Sci Technol* 42:4618–4618. doi:[10.1021/es0871614](https://doi.org/10.1021/es0871614)
2. Liu C, Hu J, Liu J (2008) Release of perfluorooctane sulfonate (PFOS) from semiconductor manufacturing site and environmental concentration estimation and environmental risk assessment of PFOS near semiconductor manufacturing site. *Sci Tech Engng* 8:2898–2902. Available at http://en.cnki.com.cn/Article_en/CJFDTOTAL-KXJS200811032.htm
3. Paul AG, Jones KC, Sweetman AJ (2008) A first global production, emission, and environmental inventory for perfluorooctane sulfonate. *Environ Sci Technol* 43:386–392. doi:[10.1021/es802216n](https://doi.org/10.1021/es802216n)

4. Pan G, Jia CX, Zhao DY, You C, Chen H, Jiang GB (2009) Effect of cationic and anionic surfactants on the sorption and desorption of perfluorooctane sulfonate (PFOS) on natural sediments. *Environ Pollut* 15:325–330. doi:[10.1016/j.envpol.2008.06.035](https://doi.org/10.1016/j.envpol.2008.06.035)
5. Zhao YG, Wong CKC, Wong MH (2012) Environmental contamination, human exposure and body loadings of perfluorooctane sulfonate (PFOS), focusing on Asian countries. *Chemosphere* 89:355–368. doi:[10.1016/j.chemosphere.2012.05.043](https://doi.org/10.1016/j.chemosphere.2012.05.043)
6. Wang T, Khim JS, Chen C (2011) Perfluorinated compounds in surface waters from Northern China: Comparison to level of industrialization. *Environ Int* 42(S):37–46. doi:[10.1016/j.envint.2011.03.023](https://doi.org/10.1016/j.envint.2011.03.023)
7. Suominen K, Hallikainen A, Ruokojärvi P (2011) Occurrence of PCDD/F, PCB, PBDE, PFAS, and organotin compounds in fish meal, fish oil and fish feed. *Chemosphere* 85:300–306. doi:[10.1016/j.chemosphere.2011.06.010](https://doi.org/10.1016/j.chemosphere.2011.06.010)
8. Lindström AB, Strynar MJ, Libelo EL (2011) Polyfluorinated compounds: past, present, and future. *Environ Sci Technol* 45:7954–7961. doi:[10.1021/es2011622](https://doi.org/10.1021/es2011622)
9. Vecitis CD, Park H, Cheng J, Mader BT, Hoffmann MR (2009) Treatment technologies for aqueous perfluorooctanesulfonate (PFOS) and perfluorooctanoate (PFOA). *Front Environ Sci Eng* 3:129–151. doi:[10.1007/s11783-009-0022-7](https://doi.org/10.1007/s11783-009-0022-7)
10. Tang CYY, Fu QS, Robertson AP, Criddle CS, Leckie JO (2006) Use of reverse osmosis membranes to remove perfluorooctane sulfonate (PFOS) from semiconductor wastewater. *Environ Sci Technol* 23:7343–7349. doi:[10.1021/Es060831q](https://doi.org/10.1021/Es060831q)
11. Hori H, Nagaoka Y, Yamamoto A (2006) Efficient decomposition of environmentally persistent perfluorooctanesulfonate and related fluorochemicals using zerovalent iron in subcritical water. *Environ Sci Technol* 40:1049–1054. doi:[10.1021/Es0517419](https://doi.org/10.1021/Es0517419)
12. Rebitzer G, Ekvall T, Frischknecht R (2004) Life cycle assessment Part 1: framework, goal and scope definition, inventory analysis, and applications. *Environ Int* 30:701–720. doi:[10.1016/j.envint.2003.11.005](https://doi.org/10.1016/j.envint.2003.11.005)
13. Ekvall T, Weidema BP (2004) System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Ass* 9:161–171. doi:[10.1065/lca2004.03.148](https://doi.org/10.1065/lca2004.03.148)
14. Suer P, Nilsson-Paledal S, Norrman J (2004) LCA for site remediation: a literature review. *Soil Sediment Contam* 13:415–425. doi:[10.1080/10588330490471304](https://doi.org/10.1080/10588330490471304)
15. Diamond ML, Page CA, Campbell M (1999) Life-cycle framework for assessment of site remediation options: method and generic survey. *Environ Toxicol Chem* 18:788–800. doi:[10.1897/1551-5028\(1999\)018<0788:LCFFAO>2.3.CO;2](https://doi.org/10.1897/1551-5028(1999)018<0788:LCFFAO>2.3.CO;2)
16. Jolliet O, Margni M, Charles R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. *Int J Life Cycle Ass* 8:324–330. doi:[10.1007/BF02978505](https://doi.org/10.1007/BF02978505)
17. Cinici H, Karacif K, Kafkas F (2011) Effect of electrolytic nickel coating on fatigue life of iron based powder metal parts. *Kovove Mater* 49:355–359. doi:[10.4149/km_2011_5_355](https://doi.org/10.4149/km_2011_5_355)
18. Pennington DW, Margni M, Amman C, Jolliet O (2005) Spatial versus non-spatial multimedia fate and exposure modeling: insights for Western Europe. *Environ Sci Technol* 39:1119–1128. doi:[10.1021/es034598x](https://doi.org/10.1021/es034598x)
19. Dockery DW, Pope CA (1994) Acute respiratory effects of particulate pollution. *Annu Rev Publ Health* 15:107–132. doi:[10.1146/annurev.publhealth.15.1.107](https://doi.org/10.1146/annurev.publhealth.15.1.107)
20. Crettaz P, Pennington D, Rhomberg L, Brand B, Jolliet O (2002) Assessing human health response in life cycle assessment using ED10s and DALYs: part 1-cancer effects. *Risk Anal* 22:931–946. doi:[10.1111/1539-6924.00262](https://doi.org/10.1111/1539-6924.00262)
21. IPCC (2001). Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change, pp 385–391. Available at http://www.grida.no/climate/ipcc_tar/
22. Hu XT, Zhu JX, Ding Q (2011) Environmental life-cycle comparisons of two polychlorinated biphenyl remediation technologies: incineration and base catalyzed decomposition. *J Hazard Mater* 191:258–268. doi:[10.1016/j.jhazmat.2011.04.073](https://doi.org/10.1016/j.jhazmat.2011.04.073)
23. Zhu JX, Xie YJ, Zhang FS (2012) Life cycle analysis for PFOS decomposition in supercritical water. *Procedia Environ Sci* 16:304–310. doi:[10.1016/j.proenv.2012.10.043](https://doi.org/10.1016/j.proenv.2012.10.043)