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## Life cycle assessment of sewage sludge treatment in China

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# Life cycle assessment of sewage sludge treatment in China

Xin Wang<sup>1</sup>, Fuyang Yu<sup>2</sup>, Qingxin Fan<sup>1,\*</sup>

<sup>1</sup>School of Harbin Institute of Technology, Harbin, China.

<sup>2</sup>Ecological Environment Technology Support Center of Heilongjiang Province, Harbin, China.

\*Corresponding author e-mail: fanqingxin@hit.edu.com

**Abstract.** Taking sewage sludge (SS) as the research object, establish 6 scenarios of sludge treatment, S1: concentration and dehydration-cement preparation ( $C_dC_{pd}$ ); S2: concentration and dehydration-lime stable-cement preparation ( $C_dL_sC_{pd}$ ); S3: concentration and dehydration-drying-landfill ( $C_dD_rL$ ); S4: concentration and dehydration-drying-incineration-landfill ( $C_dD_rIL$ ); S5: concentration and dehydration-drying-incineration-concrete preparation ( $C_dD_rIC_p$ ); S6: concentrate-anaerobic digestion-land use ( $CAL_u$ ), LCA is used to compare the environmental impacts of S1-S6 in China, find the unit that has a greater impact on environment in different treatments and substances and energy that have a greater impact on the environment in different units. The results show that the environmental impacts dealing with 1t SS (water content 80%) can be sequenced as  $S3 > S4 > S5 > S6 > S1 > S2$ ; the direct pollutants generated in the unite of direct landfill and incineration and the thermal energy required for drying have a great impact on the environment; after a series of treatments of SS for concrete preparation and cement preparation, that is, resource utilization can fix certain elements in the sludge, so that the environmental impact can be alleviated; the transfer of contaminants during the SS treatment process is a matter of concern, so that the focus of the SS treatment should be on the fixation of pollutants in the future.

## 1. Introduction

SS is a mixture of black or dark brown fluids with a moisture content of 75% to 99% produced by sewage treatment plants after completion of sewage purification. It is composed of organic residues, bacterial cells, inorganic particles, pathogens, parasite eggs, colloids and heavy metals [1, 2]. It is predicted that the sludge production of SS in China will reach  $6 \times 10^7$ - $9 \times 10^7$ t by 2020 [3]. Due to the complex composition of SS, it is easy to cause secondary pollution to the atmosphere, water body, soil ecological environment and human health, and simple stacking damages the image of the city. At present, SS treatment methods mainly include SS composting, landfilling and incineration at home and abroad [4]. In addition, SS can also be used to prepare for building materials such as cement and concrete. The treatment process of SS is an environmental protection project, but it also has environmental impacts, including the indirect effects of the production and use of materials, energy such as electricity, heat, chemicals and so on, and the direct impact of the transfer of pollutants in SS. As a tool for environmental impact analysis, LCA [5] can be taken into account both direct environmental impacts and indirect environmental impacts from a life cycle perspective. Since the beginning of the 21st century, Sue [6] and others used LCA for comparative research on sludge incineration, landfill and land use in France.



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From then on, many scholars have conducted research in this area at home and abroad. In China, Yanfen Liao [7], Hong [8], Yaqing Qi [9], Hongtao Liu [10], Changqing Xu [11], Yanyan Yuan [12], Qianyun Zhang [13] and Guanyi Chen [14] conducted a large number of comparative studies on traditional SS treatments including landfill, incineration, and land use. In addition, Xijun Shi [15] and Domagoj [16] studied separately the environmental impact of SS used for preparation of building materials, including cement and concrete.

In this paper, LCA is used to compare the environmental impacts of S1-S6 including: traditional landfill, incineration, land use and preparation of cement and concrete, then analyze the treatment unit that has a greater impact on environment in six scenarios and the substances and energy that have a greater impact on the environment in different units.

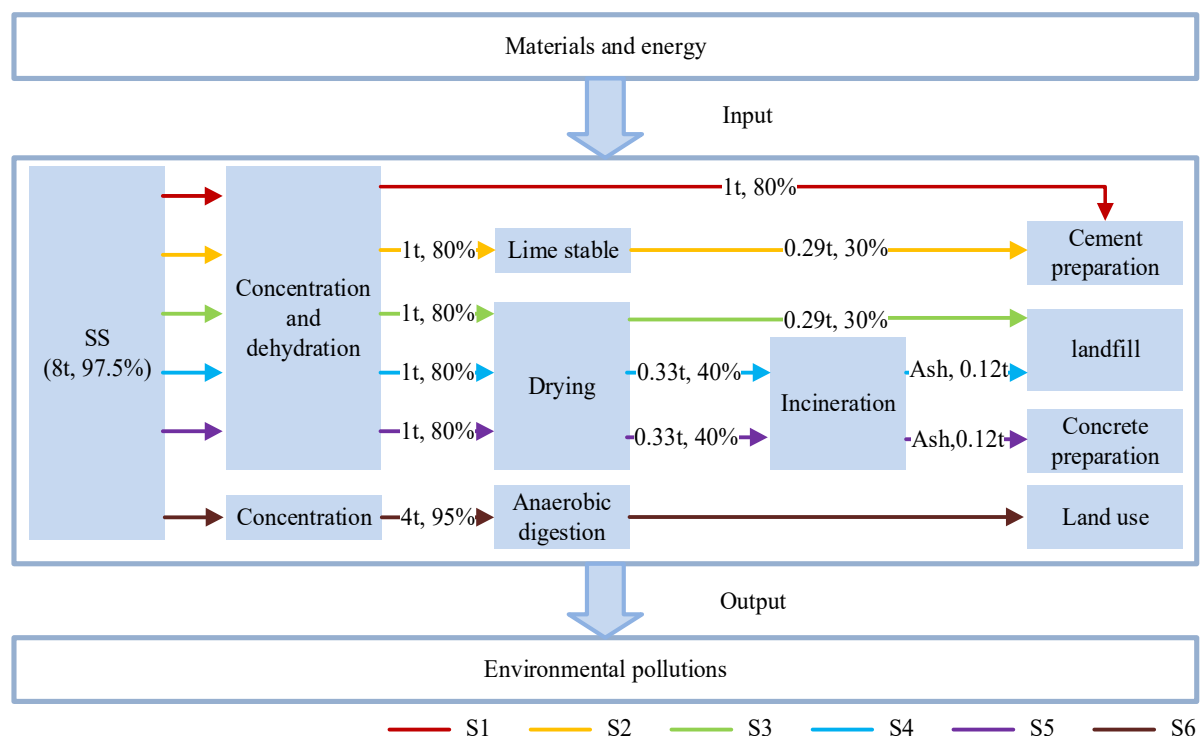
## 2. SS treatment scenario establishment and acquisition of input and output lists

### 2.1. Functional unit

Functional unit provides a unified baseline for metering inputs and outputs for life cycle assessment. In this paper, 1t SS with a moisture content of 80% is used as a functional unit. The conversion of raw material consumption, input and output, energy consumption and recovery for all SS treatment processes are based on the functional unit.

### 2.2. Scenario study description

Six scenarios are founded, S1: Concentration and dehydration-cement preparation ( $C_dC_{pd}$ ); S2: Concentration and dehydration-lime stable-cement preparation ( $C_dL_sC_{pd}$ ); S3: Concentration and dehydration-drying-landfill ( $C_dD_rL$ ); S4: Concentration and dehydration-drying-incineration-landfill ( $C_dD_rIL$ ); S5: Concentration and dehydration-drying-incineration-concrete preparation of ( $C_dD_rIC_p$ ); S6: concentrate-anaerobic digestion-land use ( $CAL_u$ ). Figure 1 shows the system boundary of S1-S6. The environmental impact of transportation is not taken into consideration.



Note: The data at the connection line shows the amount of sludge and moisture content.

**Figure 1.** System boundary.

### 2.3. Life-cycle inventory

Life-cycle inventory (LCI) usually serves a fundamental function in LCA analysis [11]. The input and output lists of substances and energy of S1-S6 in this paper are from Hong [8], Changqing Xu [11], Qianyun Zhang [13], Xijun Shi [15], and Domagoj [16] and the best available techniques directive of sewage sludge treatment in China [17].

There are some instructions for the inventory data.

(1) All the conversion of raw material consumption, input and output, energy consumption and recovery for all SS treatment processes are based on the functional unit.

(2) Convert the data proportionally if it does not fit the functional unit.

(3) Derive the data from actual engineering in China, calculation, then foreign data.

(4) SS can replace some sandstone and cement when it is used to prepare cement and concrete, which reduces the environmental impact of the use of materials. Therefore, sandstone and cement are regarded as output materials in these processes.

According to the data selection principles and references mentioned above, the data lists of S1-S6 are shown from Table 1 to Table 6.

**Table 1.** Life-cycle inventories of S1

	classification	Item	Unite	Quantity	Item	Unit	Quantity
$C_d$	Input	Electricity	kWh	$1.20 \times 10^1$	PAM	kg	$6.00 \times 10^{-1}$
	Output	Wastewater	t	7.00			
$C_{pd}$	Input	Electricity	kWh	$1.20 \times 10^{-1}$	Coal	t	$3.20 \times 10^{-2}$
	Output	sandstone	t	$1.20 \times 10^{-2}$			

**Table 2.** Life-cycle inventories of S2

	classification	Item	Unite	Quantity	Item	Unit	Quantity
$C_d L_s$	Input	Electricity	kWh	$1.20 \times 10^1$	PAM	kg	$6.00 \times 10^{-1}$
		Lime	t	$2.00 \times 10^{-1}$			
	Output	Wastewater	t	7.00			
$C_{pd}$	Output	sandstone	t	$1.20 \times 10^{-2}$			

**Table 3.** Life-cycle inventories of S3

	classification	Item	Unite	Quantity	Item	Unit	Quantity
$C_d$	Input	Electricity	kWh	$1.20 \times 10^1$	PAM	kg	$6.00 \times 10^{-1}$
	Output	Wastewater	t	7.00			
$D_r$	Input	Electricity	kWh	$1.28 \times 10^2$	Energy	kJ	$2.53 \times 10^6$
L	Input	Insecticide	kg	$1.09 \times 10^{-2}$	Water	m <sup>3</sup>	$3.19 \times 10^{-2}$
		Electricity	kWh	$1.22 \times 10^{-1}$	LDPE	m <sup>3</sup>	$2.29 \times 10^{-5}$
		Limestone	kg	$6.38 \times 10^1$	Sand	m <sup>3</sup>	$1.19 \times 10^{-1}$
		Diesel	L	$1.10 \times 10^{-1}$			
		Electricity	kWh	$3.25 \times 10^1$			
	Output	CH <sub>4</sub>	kg	$1.34 \times 10^1$	NH <sub>3</sub>	kg	$4.00 \times 10^{-3}$
		SO <sub>2</sub>	kg	$2.20 \times 10^{-1}$	NO <sub>x</sub>	kg	$7.80 \times 10^{-2}$
		H <sub>2</sub> S	kg	$4.54 \times 10^{-3}$			
		COD	kg	8.25	T-Cd	kg	$2.00 \times 10^{-2}$
		T-Hg	kg	$2.50 \times 10^{-2}$	T-Zn	kg	4.00
		T-Cr	kg	1.00	T-Cu	kg	1.05
		T-Ni	kg	$2.00 \times 10^{-1}$	T-As	kg	$7.50 \times 10^{-2}$
		Pb	kg	1.00			

**Table 4.** Life-cycle inventories of S4

	classification	Item	Unit	Quantity	Item	Unit	Quantity
C <sub>d</sub>	Input	Electricity	kWh	1.20×10 <sup>1</sup>	PAM	kg	6.00×10 <sup>-1</sup>
	Output	Wastewater	t	7.00			
D <sub>r</sub>	Input	Electricity	kWh	1.21×10 <sup>2</sup>	Energy	kJ	2.39×10 <sup>6</sup>
I	Input	NaOH	kg	4.05	Coal	kg	4.00×10 <sup>1</sup>
		Electricity	kWh	5.50×10 <sup>1</sup>	Diesel	L	9.00
	Output	Ash	t	1.20×10 <sup>-1</sup>	NO <sub>2</sub>	kg	5.62×10 <sup>-1</sup>
		SO <sub>2</sub>	kg	2.60×10 <sup>-1</sup>	Cd	kg	1.12×10 <sup>-4</sup>
		Hg	kg	1.12×10 <sup>-4</sup>	PM <sub>10</sub>	kg	1.50×10 <sup>-1</sup>
		CO	kg	1.82×10 <sup>-1</sup>	CO <sub>2</sub>	kg	8.65×10 <sup>1</sup>
		Dioxin	kg	1.00×10 <sup>-7</sup>	Electricity	kWh	2.05×10 <sup>2</sup>
		Pb	kg	4.00×10 <sup>-2</sup>	Ni	kg	7.00×10 <sup>-1</sup>
		Zn	kg	4.00×10 <sup>-1</sup>	Cu	kg	4.00×10 <sup>-2</sup>
		Cr	kg	6.00×10 <sup>-2</sup>	Sn	kg	2.00×10 <sup>-3</sup>
L	Input	Electricity	kWh	5.04×10 <sup>-2</sup>	Water	m <sup>3</sup>	1.32×10 <sup>-2</sup>
		Insecticide	kg	4.52×10 <sup>-3</sup>	LDPE	m <sup>3</sup>	9.05×10 <sup>-6</sup>
		Limestone	kg	2.64×10 <sup>1</sup>	Sand	m <sup>3</sup>	4.92×10 <sup>-2</sup>
		Diesel	L	4.56×10 <sup>-2</sup>			
	Output	Electricity	kWh	1.34×10 <sup>1</sup>			

**Table 5.** Life-cycle inventories of S5

	classification	Item	Unit	Quantity	Item	Unit	Quantity
C <sub>d</sub>	Input	Electricity	kWh	1.20×10 <sup>1</sup>	PAM	kg	6.00×10 <sup>-1</sup>
	Output	Wastewater	t	7.00			
D <sub>r</sub>	Input	Electricity	kWh	1.21×10 <sup>2</sup>	Energy	KJ	2.39×10 <sup>6</sup>
I	Input	NaOH	kg	4.05	Coal	kg	4.00×10 <sup>1</sup>
		Electricity	kWh	5.50×10 <sup>1</sup>	Diesel	L	9.00
	Output	Electricity	kWh	2.05×10 <sup>2</sup>	NO <sub>2</sub>	kg	5.62×10 <sup>-1</sup>
		SO <sub>2</sub>	kg	2.60×10 <sup>-1</sup>	Cr	kg	6.00×10 <sup>-2</sup>
		Hg	kg	1.12×10 <sup>-4</sup>	PM <sub>10</sub>	kg	1.50×10 <sup>-1</sup>
		CO	kg	1.82×10 <sup>-1</sup>	CO <sub>2</sub>	kg	8.65×10 <sup>1</sup>
		Dioxin	kg	1.00×10 <sup>-7</sup>	Sn	kg	2.00×10 <sup>-3</sup>
		Pb	kg	4.00×10 <sup>-2</sup>	Ni	kg	7.00×10 <sup>-1</sup>
		Zn	kg	4.00×10 <sup>-1</sup>	Cu	kg	4.00×10 <sup>-2</sup>
C <sub>p</sub>	Output	cement	kg	2.00×10 <sup>2</sup>			

**Table 6.** Life-cycle inventories of S6

	classification	Item	Unit	Quantity	Item	Unit	Quantity
C	Input	Electricity	kWh	4.68	PAM	kg	3.00×10 <sup>-1</sup>
	Output	Wastewater	t	4.00			
A	Input	Electricity	kWh	7.90×10 <sup>1</sup>			
	Output	Electricity	kWh	8.89×10 <sup>1</sup>	N <sub>2</sub> O	kg	1.33
L <sub>u</sub>	Output	CH <sub>4</sub>	kg	1.80×10 <sup>1</sup>			
		Cd	kg	1.61×10 <sup>-4</sup>	Hg	kg	7.05×10 <sup>-4</sup>
		Pb	kg	5.74×10 <sup>-4</sup>	As	kg	7.81×10 <sup>-4</sup>
		Ni	kg	5.65×10 <sup>-3</sup>	Zn	kg	2.97×10 <sup>-4</sup>
		Cu	kg	3.41×10 <sup>-5</sup>	NO <sub>x</sub>	kg	7.80×10 <sup>-5</sup>
		mineral oil	kg	2.28×10 <sup>-4</sup>			

### 3. Results

There are many methods for life cycle impact assessment such as EDP2003, EPS2000, Eco-indicator99, CML2001 and so on. CML2001 is a method published by the Environmental Research Center of Leiden

University in 2001. The impact of this method is divided into three parts, including material, energy consumption and damage to pollution. The specific classification of this method is shown in Table 7 [18]. The method is a problem-oriented approach based on traditional life cycle inventory analysis features and standardized methods. The use of intermediate point analysis reduces the number of hypotheses and the complexity of the model.

**Table 7.** Types and classification of environmental impacts in the CML2001 method

Environmental impact type	Characterization factor	Major pollutant
Abiotic Depletion (ADP elements)	kg Sb	Minerals, chemical elements
Abiotic Depletion (ADP fossil)	MJ	fossil fuel
Acidification Potential (AP)	kg SO <sub>2</sub>	CO <sub>2</sub> , NO <sub>x</sub> , CH <sub>4</sub> , CO, etc.
Eutrophication Potential (EP)	kg Phosphate	PAM, etc.
Freshwater Aquatic Ecotoxicity Potential (FAETP inf.)	kg DCB	Toxic Chemicals
Global Warming Potential (GWP)	kg CO <sub>2</sub>	Hg, Cd, Cu, etc.
Human Toxicity Potential (HTP)	kg DCB	C <sub>2</sub> H <sub>4</sub> , CO, SO <sub>2</sub> , NO <sub>x</sub> , etc.
Marine Aquatic Ecotoxicity Potential (MAETP inf.)	kg DCB	Hg, Cd, Cu, etc.
Ozone Layer Depletion Potential (ODP, steady state)	kg R11	Hg, Cd, Cu, Pathogen, etc.
Photochem, Ozone Creation Potential (POCP)	kg Ethene	NH <sub>3</sub> , NO <sub>2</sub> , SO <sub>2</sub> , etc.
Terrestrial Ecotoxicity Potential (TETP inf.)	kg DCB	COD, N, P, etc.

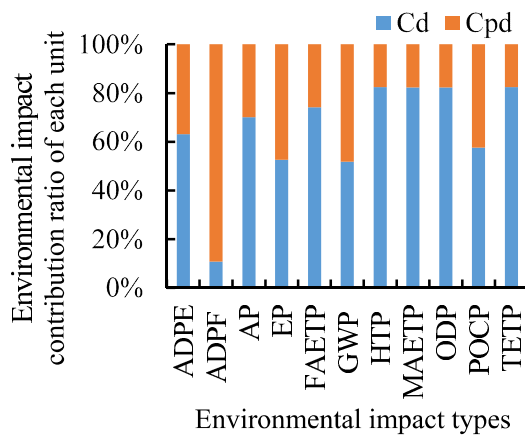
This paper adopts the CML2001 analysis method. The LCIA results of the six scenarios in China are obtained through the standardized process of life cycle assessment, and shown in Table 8. The treatment units that have a greater impact on environment in different scenarios, and substances and energy that have a greater impact on the environment in different units will be analyzed next.

**Table 8.** CML2001 mid-point results for S1-S6. Values are presented per functional unit.

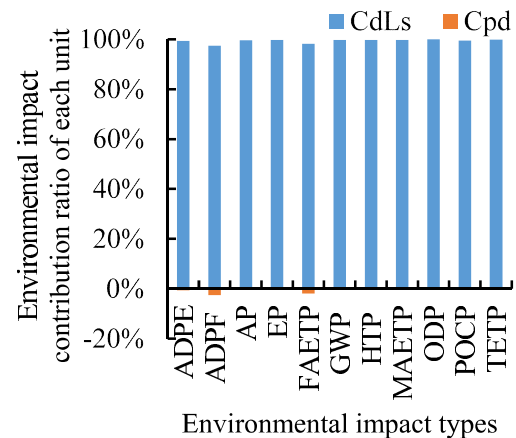
Categories	S1	S2	S3	S4	S5	S6
ADPE	$2.57 \times 10^{-14}$	$2.32 \times 10^{-14}$	$6.33 \times 10^{-13}$	$1.03 \times 10^{-12}$	$-3.64 \times 10^{-12}$	$-7.05 \times 10^{-15}$
ADPF	$1.78 \times 10^{-11}$	$2.06 \times 10^{-12}$	$2.30 \times 10^{-10}$	$6.95 \times 10^{-11}$	$7.16 \times 10^{-11}$	$-8.33 \times 10^{-13}$
AP	$1.59 \times 10^{-12}$	$1.24 \times 10^{-12}$	$1.66 \times 10^{-09}$	$3.30 \times 10^{-11}$	$2.41 \times 10^{-11}$	$-2.98 \times 10^{-13}$
EP	$2.51 \times 10^{-13}$	$1.88 \times 10^{-13}$	$5.87 \times 10^{-10}$	$5.91 \times 10^{-12}$	$4.39 \times 10^{-12}$	$1.49 \times 10^{-11}$
FAETP	$3.91 \times 10^{-13}$	$3.00 \times 10^{-13}$	$2.29 \times 10^{-08}$	$8.12 \times 10^{-12}$	$8.35 \times 10^{-12}$	$2.99 \times 10^{-11}$
GWP	$4.43 \times 10^{-12}$	$2.51 \times 10^{-12}$	$5.68 \times 10^{-10}$	$7.38 \times 10^{-11}$	$5.18 \times 10^{-11}$	$1.88 \times 10^{-10}$
HTP	$1.22 \times 10^{-11}$	$1.02 \times 10^{-11}$	$4.15 \times 10^{-09}$	$8.14 \times 10^{-10}$	$7.60 \times 10^{-10}$	$1.31 \times 10^{-10}$
MAETP	$8.26 \times 10^{-11}$	$6.98 \times 10^{-11}$	$1.03 \times 10^{-07}$	$1.48 \times 10^{-09}$	$1.55 \times 10^{-09}$	$2.09 \times 10^{-10}$
ODP	$7.12 \times 10^{-20}$	$7.58 \times 10^{-20}$	$1.99 \times 10^{-18}$	$6.25 \times 10^{-20}$	$1.25 \times 10^{-19}$	$-2.55 \times 10^{-20}$
POCP	$1.27 \times 10^{-12}$	$8.12 \times 10^{-13}$	$2.16 \times 10^{-10}$	$2.10 \times 10^{-11}$	$1.77 \times 10^{-11}$	$1.88 \times 10^{-11}$
TETP	$6.53 \times 10^{-13}$	$5.87 \times 10^{-13}$	$1.53 \times 10^{-08}$	$3.22 \times 10^{-11}$	$3.15 \times 10^{-11}$	$2.71 \times 10^{-10}$
TEIP	$1.21 \times 10^{-10}$	$8.77 \times 10^{-11}$	$1.49 \times 10^{-07}$	$2.53 \times 10^{-09}$	$2.52 \times 10^{-09}$	$8.61 \times 10^{-10}$

Note: TEIP in the table represents the total environmental impact potential

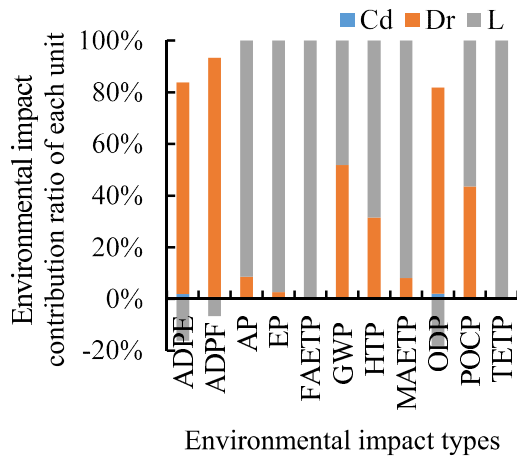
In order to analyze the environmental impact of S1-S6 more clearly, the results are plotted as Figure 2 to Figure 8.



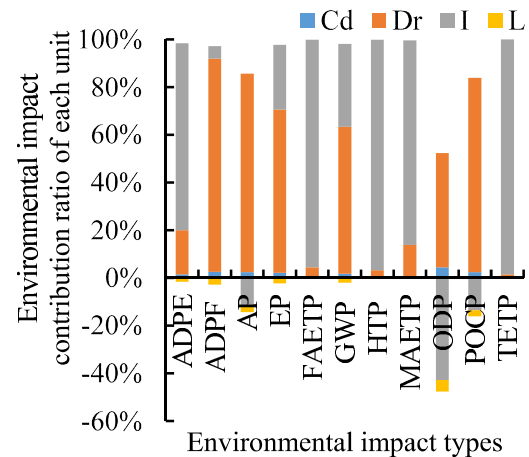
**Figure 2.** Contributions of sludge treatment processes to mid-point value of S1.



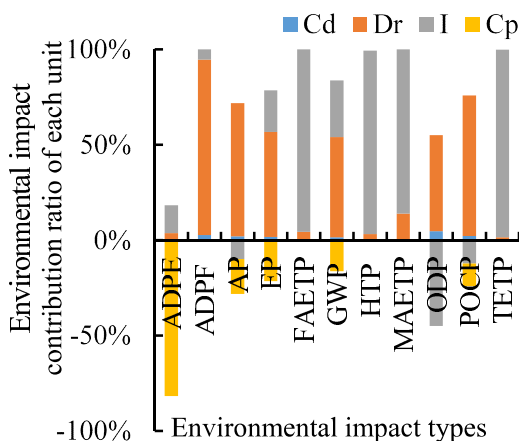
**Figure 3.** Contributions of sludge treatment processes to mid-point value of S2.



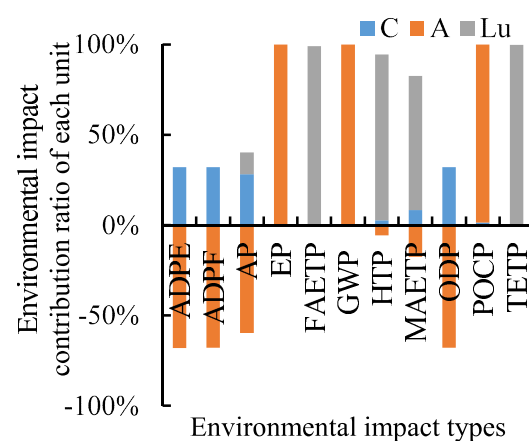
**Figure 4.** Contributions of sludge treatment processes to mid-point value of S3.



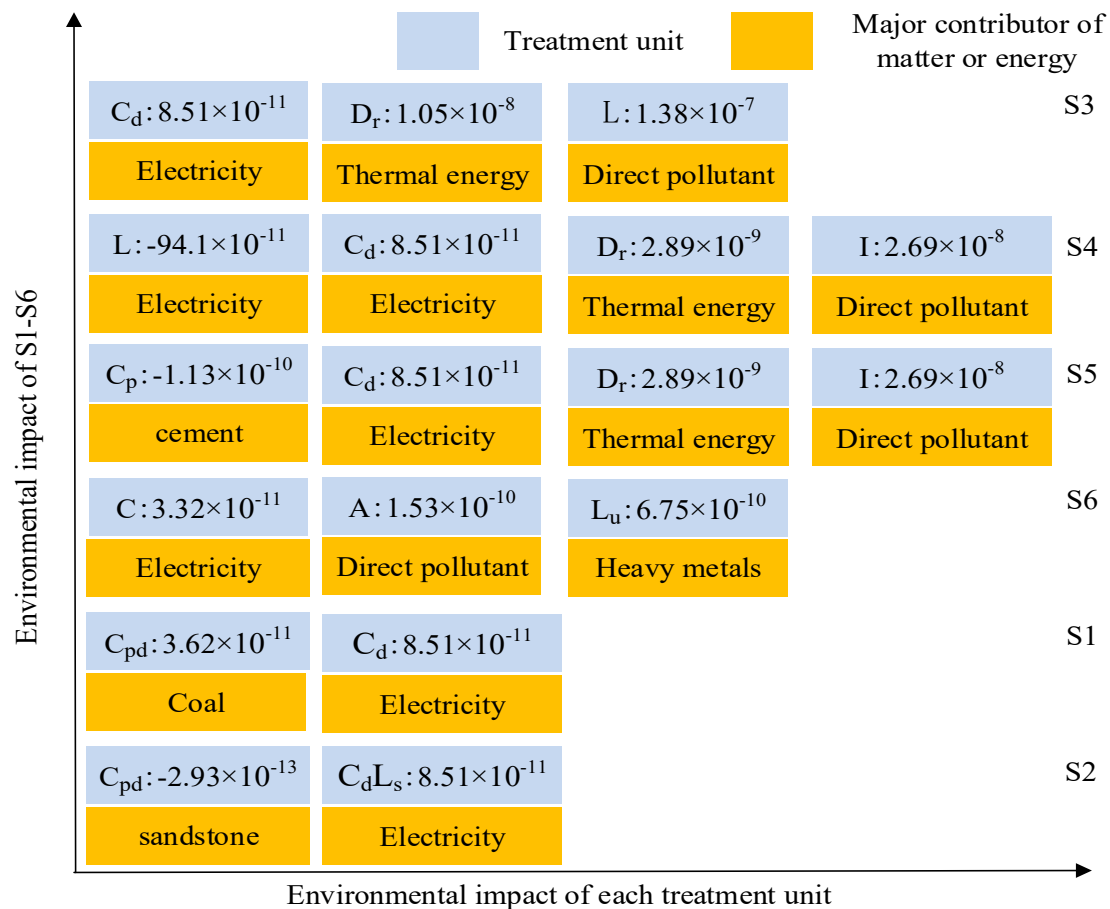
**Figure 5.** Contributions of sludge treatment processes to mid-point value of S6.



**Figure 6.** Contributions of sludge treatment processes to mid-point value of S5.



**Figure 7.** Contributions of sludge treatment processes to mid-point value of S6.



**Figure 8.** Comprehensive analysis of life cycle environmental impact of S1-S6.

Figures 2 to Figure 7 show the contribution ratios of the different treatment units for each scenario to the 11 environmental impact types included in CML2001. In Figure 8, the ordinate indicates the comparison of the environmental impacts of the different scenarios, the abscissa indicates the environmental impact of the different units in each scenario and the substances or energy that has the biggest environmental impact in each unit. It is can be seen from Figure 2 to Figure 8.

(1) The environmental impacts dealing with 1t SS (water content 80%) can be sequenced as S3 ( $1.49 \times 10^{-7}$ ) > S4 ( $2.98 \times 10^{-8}$ ) > S5 ( $2.97 \times 10^{-8}$ ) > S6 ( $8.61 \times 10^{-9}$ ) > S1 ( $1.21 \times 10^{-10}$ ) > S2 ( $8.77 \times 10^{-11}$ ).

(2) The substances and energy that have a great impact on environment in S1 are the electricity consumption in the process of concentration and dehydration and the coal consumption in the process of preparing for cement.

(3) The substances and energy that have a great impact on environment in S2 are the electricity consumption in the process of concentration and dehydration. Using SS to prepare cement can reduce the use of sandstone and reduce environmental pollution.

(4) The substances and energy that have a great impact on environment in S3 are the thermal energy consumption in the process of drying treatment and the direct pollutants generated during the process of landfill.

(5) The substances and energy that have a great impact on environment in S4 are the thermal energy consumption in the process of drying treatment and the direct pollutants generated during the incineration treatment process. It can be seen that, the transfer process of elements in SS is of vital importance compared with S3. Power generation in the process of landfill is beneficial for the environment.



(6) The substances and energy that have a great impact on environment in S5 are the same with S4. Moreover, using ash as cement to prepare concrete is beneficial for the environment.

(7) The substances and energy that have a great impact on environment in S6 are the greenhouse gases emitted during anaerobic digestion and the heavy metals emitted during land use.

It can be seen from the upper right corner of Figure 8 that the direct pollutants generated during the incineration process and the thermal energy required for the drying process have a great impact on environment. Besides it can be seen from the lower left corner of Figure 8 that the SS treated after certain treatments used to prepare cement and concrete can fix certain elements in SS to reduce environmental impact. Therefore, it is important to increase the resource utilization rate of the SS to fixed as many pollutant substances as possible.

#### 4. Conclusion

The paper takes SS as the research object, analyzes 6 treatment scenarios of SS. After the above analysis, the following conclusions are reached.

(1) The environmental impacts dealing with 1t SS (water content 80%) can be sequenced as S3> S4> S5>S6> S1> S2. That shows the environmental impact of sludge drying, incineration and direct landfill is relatively larger than other treatment units.

(2) The direct pollutants generated in the unite of direct landfill and incineration and the thermal energy required for drying have a great impact on the environment.

(3) After a series of treatments of SS for concrete preparation and cement preparation, that is, resource utilization can fix certain elements in the sludge, so that the environmental impact can be alleviated.

(4) The transfer of contaminants during the SS treatment process is a matter of concern, so that the focus of the SS treatment should be on the fixation of pollutants in the future to reduce the environmental impacts.

#### Acknowledgments

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