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Life Cycle Impacts of Flexible-fiber Deep-bed Filter Compared to Sand-Filter including Coagulation and Sedimentation in Water Treatment Plant

Soo-gap Uh, Ji-won Kim[1], Kiback Han[2], and Changwon Kim[3,†]

Environmental Management Corporation, Environmental Research Complex, Kyoungseo-dong, Incheon 404-708, Korea
[1]Department of Civil & Environmental Engineering, Ulsan University, San 29 Muger 2-dong Nam-gu, Ulsan 680-749, Korea
[2]nanoENtech Co., Ltd. Sanmackdong 371-2 Yangsan city, Kyungnam 626-120, Korea
[3]Department of Environmental Engineering, Pusan National University, 30 Jang-jeon dong, Geumjeong-gu, Busan 609-735, Korea

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Abstract

Recently a new technology called the flexible-fiber deep-bed filter (FDF) claimed to replace the conventional sand filter including coagulation and sedimentation filter (CSF) processes in the water treatment plant. Therefore the life cycle assessment (LCA) approach was applied for evaluating the life cycle impacts of FDF compared with those of CSF. The used LCA softwares were the Simapro 6 and PASS and their life cycle impact assessment (LCIA) methodologies were the Eco-indicator 99 and the Korean Eco-indicator, respectively. The goal of this LCA was to identify environmental loads of CSF and FDF from raw material to disposal stages. The scopes of the systems have been determined based on the experiences of existing CSF and FDF. The function was to remove suspended solids by filtration and the functional unit was 1 m^3/day. Both systems showed that most environmental impacts were occurred during the operation stage. To reduce the environmental impacts the coagulants and electricity consumptions need to be cut down. If the CSF was replaced with the FDF, the environmental impacts would be reduced in most of the impact categories. The LCA results of Korean Eco-indicator and Eco- indicator99 were quite different from each other due to the indwelling differences such as category indicators, impact categories, characterization factors, normalization values and weighting factors. This study showed that the life cycle assessment could be a valuable tool for evaluating the environmental impact of the new technology which was introduced in water treatment process.

Keywords: LCA, Simapro, PASS, Water treatment, Flexible-fiber deep-bed Filter

1. Introduction

The industries should consider the environmental aspects as well as the economic development together when they develop new technologies. They also concern not only immediate environmental pollution but also life cycle environmental impacts of their products and services. The life cycle assessment (LCA) is a representative tool that evaluates systematically the potential environmental impacts of a product, service and process throughout their entire life cycle.[1,2] It can quantify and analyse the use of resources, environmental emissions and environmental impacts associated with the concerning systems. The LCA method consists of 4 phases including goal and scope definition, life cycle inventory analysis, life cycle impact assessment (LCIA), and interpretation of the results. The procedures to carry out these tasks are described well in the ISO14000 series and the manuals of specific LCA tools.[3,4]

The water treatment field has not been exceptional in this respect. Usually the new technology has been evaluated based on how much it improves the water quality or how much it reduces the operating and management cost. However, these criteria are not enough for considering the environmental impacts during construction, operation and disposal period of the technologies. Therefore the LCA could be a promising alternative and it is becoming accepted more and more for evaluating new technologies.

Recently a flexible-fiber deep-bed filter (FDF) was introduced as a new technology to remove suspend solids for drinking water treatment. One may find out the characteristics of this FDF at the following section and or at the manufacturer's homepage.[5] It claimed that it performed very high removal efficiency. Therefore it could replace conventional sand filtration units which was proceeded by coagulation and sedimentation at the water treatment plants. The coagulation, sedimentation, and sand filteration processes were represented as CSF. In order to demon-

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[†] Corresponding author
E-mail: cwkim@pusan.ac.kr
Tel: 051-510-2416, Fax: 051-515-5347

strate its superiority in terms of not only technical performance but also environmental impacts during its entire life cycle the LCA was considered as a useful tool.

There are many LCA softwares available as commercial products which use somewhat different life cycle impact assessment (LCIA) methodologies.[6,7] In this research two LCA softwares were used and they use different LCIA methodologies. The adopted LCA softwares were the Simapro 6 (Pre consultant, Netherlands, 2004) and PASS (Product Assessment for Sustainable Solutions), and their LCIA methodologies were Eco-indicator 99[8] and Korean Eco-indicator,[9] respectively. The Simapro and the Eco-indicator 99 are well accepted over the world. However the PASS and the Korean Eco-indicator were developed recently based on Korean circumstances, and their application was relatively limited.

The objectives of this research were two folds. First it was to identify the environmental loads of CSF and FDF from raw material to disposal stages and to assess the environmental impacts of those systems in the water treatment plant using two LCA tools. Second, it was attempted to demonstrate the superiority of FDF against to the CSF in terms of its life cycle environmental impacts.

2. Materials and Methods

The target products for life cycle assessment in this work were FDF and CSF.

The FDF was made of stainless steel tube which was packed with the flexible fiber. The additional components included pump, compressor, and air tank. The schematic diagram is shown in the Fig. 1. The treatment capacity of FDF used in this research was 61,631 m^3/day.

The CSF was consisted of coagulation tank, settling tank, sand filter and several pumps. The schematic diagram of CSF is shown in the Fig. 2 as a part of a whole water treatment processes. Total capacity of the Ducksan water treatment plant, Busan, Korea used in this research was 751,886 m^3/d.

The characteristics of existing sand filter and FDF were compared in the Table 1. The FDF had about 5~10 times higher filtration velocity which led much less back-washing water and lower operating pressure.

The tested LCA tools were SimaPro and PASS, and their LCIA methodologies were the Eco-indicator 99 and the Korean Eco-indicator, respectively. For the inventory analysis the background data were obtained from the Korean National LCI database[10] and a few data from the Ecoinvent and ETH-ESU 96. The foreground data were collected at the Ducksan water treatment plant, the manufacturer of FDF[5] and their related resources from 2004 to 2005.

The LCA was conducted according to the usual procedures including defining goal and scope, inventory analysis, impact assessment, and interpretation. The life cycle impact assessment

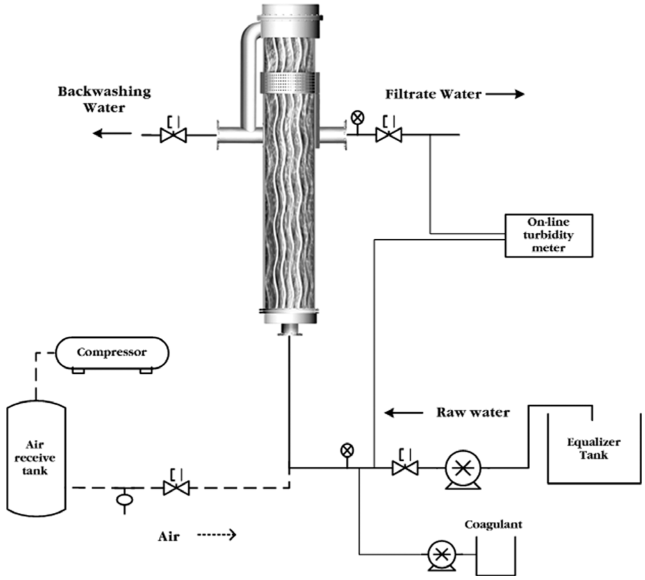

Fig. 1. Outline of fiber deep bed filter.

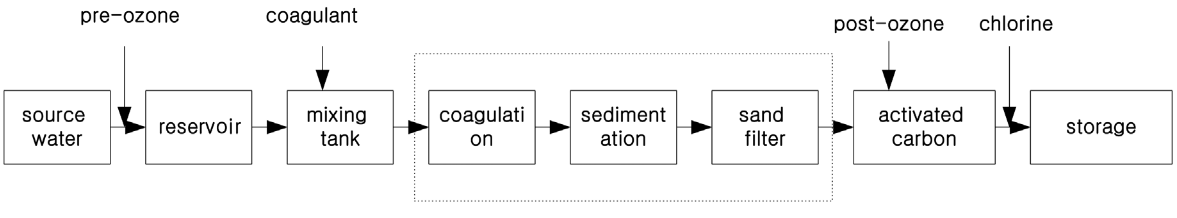

Fig. 2. Flowchart of typical advanced water treatment.

Table 1. Comparison of characteristics between existing sand filter and flexible-fiber deep-bed filter

	Existing sand filter	Flexible-fiber deep-bed filter
Filtration character	Surface filtration	Deep-bed filtration
Filtration velocity ($m^3/m^2/d$)	200~500	1,000~6,000
Back-washing water (% of treated water)	about 5%	about 1%
Operating pressure (kg/cm^2)	about 2 kg/cm^2	about 0.5 kg/cm^2
Distinctive marks	· Large site required · Channeling · Outflow of sand · Difficult to change sands	· Less site required · Less channeling · No outflow of fibers · Easy to change fibers

was consisted of four stages such as classification, characterization, normalization, and weighting. These procedures were governed by the LCIA methodologies, the Korean Eco-indicator and the Eco-indicator 99 in this research.

3. Results and Discussions

3.1. Defining Goal and Scope

The goal of this LCA was to identify environmental loads of CSF and FDF from raw material to disposal stages and to assess the environmental impacts of those in the water treatment plant. So one can use this result for eco-design of water treatment processes to reduce environmental load and resource consumption.

The scope of the systems have been determined based on the experiences of existing CSF located at the Duksan water treatment plant, Busan, Korea as a typical case. Also the FDF (model No. C009, nanoENtech Co., Ltd) installed at the Yangsan sewage treatment plant, Yangsan, Korea were used for this purpose. The function of these products was to remove suspended solids (SS) by filtration. The functional unit was determined based on the capacity to treat influent water flow, and therefore it was 1 m^3/day.

System boundary was selected based on considering only a few important parts of the life cycle including the stages of construction, operation and disposal of the products. The data category were the inputs such as raw material, ancillary material, fuel, and energy and the outputs including product, co-product, and emissions into air, water and soil.

The impact categories were identified as abiotic resource depletion (ARD), global warming (GW), ozone layer depletion (OD), acidification (AC), eutrophication (EU), photochemical oxidant creation (POC), eco toxicity (ET), and human toxicity (HT) in the Korean Eco-indicator. In the Eco-indicator 99 the impact categories were carcinogens, respiratory organics, respiratory in-organics, climate change, radiation, ozone layer, eco-toxicity, acidification-eutrophication, land-use, minerals, and fossil fuels.

3.2. Life Cycle Inventory Analysis

3.2.1. Construction Stage

The data for major input materials and electricity and fuel for the construction equipments were collected as explained at following.

CSF : The typical constructions for water works were classified into public works, construction works, electric works, and clean water machinery works. Public and construction works were divided into site readjustment work, facility work, and clean water equipment appurtenant work. The foreground data were collected from the construction specification of the Ducksan water plant, which was shown in the Table 2.

Total treatment capacity was used for converting the materials usage based on functional unit. The construction period was estimated to be 1 year, which was from April 1983 to March 1984. The working hours were calculated based on 5 days in a week and 8 hours in a day working. Total fuel and electricity usage were calculated and presented in the Table 3.

FDF : The FDF was consisted of tube-type body and fiber filter as its major parts. The major materials for manufacturing FDF were stainless steel which was used for body, fiber fixing plate, flange, cap, stub end, disk, pipe and 90 degree elbow. Additional materials were rubber for gasket and the nylon fiber for filter. The components of FDF included the air tank, the compressor, the pump, the electric panel and many valves.

The foreground data for input material of FDF was collected from the manufacturer, which was shown in the Table 4. The fuel and electric power used at the manufacturing period were utilized for bending and welding process of stainless steel and fume process of the fiber, which were shown in the Table 5.

3.2.2. Operation Stage

During the operation period for CSF and FDF, the amount of

Table 2. Materials of public works in Ducksan water treatment plant

Step	Facility	Cement (sack)	Remicon (m^3)	Reinforced steel (ton)	Steel pipe (m)	
					ϕ300 mm	ϕ400 mm
1st channel	Landing on the water	1,026	746	62	1,170	
	Sediment	19,710	12,572	1,564	16,000	
	Filter bed	10,384	2,880	260		
	Filter roof	1,105	205	21		
	Sediment	838	57	8		
	2nd, 3rd channel					
	Total	93,179	44,820 m^3	5,295 kg	25,930 m	21,924 m
Weight/F.U. (1 m^3/d)		3.88 E - 4 kg	4.67 E - 6 m^3	5.51 E - 4 kg	4.28E - 4 kg	

Table 3. Fuel and electricity at construction of Ducksan water treatment plant

Construction equipment	No.	Fuel	Consumption	Total	F.U. (1 m^3/d)
Diesel hammer (2.2 ton) Electric generator (30 kw)	1	Power	30 kw	62,400 Kwh	6.50 E - 6 Kwh
Pile driver (K25)	1	Gasoline	9~12 L/h	21,840 L	2.27 E - 6 L
		Lubricant	1.5 L/h	3120 L	3.25 E - 7 L

Table 4. Major materials of the FDF module

Module type	Total weight	Stainless steel	Rubber	Nylon fiber
C009	1100kg	988.2kg	5.9kg	105.9kg

Table 5. Usage of electricity for Nylon false twist unit

		Power (KW)	
Motor	Main	45	-
	Traverse	5.5	-
	Fume	4	-
	Yarn suction	3	-
Heater		50.04	1.39*36 EA
Total		107.54	

cf1) day average consumed : 2,457.912 KW

cf2) fume products per day : 1,440 kg

- moter & heater use 107.54 KW * 8 h = 806.32 KWh (8 hr operation/day assume)
- power of providing Nylon 106 kg => 806.32*(106 kg/1440 kg) = 89.59 Kwh

electricity consumption, coagulant consumption, and sludge production were considered. The life period of the construction structure was determined to be 35 years according to the Korean law for local public corporation.[11] The life period of the flexible fiber in the FDF was determined to be 3 years according to the manufacture's experience. Other materials in the FDF were considered as the construction structure.

CSF : The electricity consumption was 758 kW/day. The coagulant used at the Ducksan water treatment plant was PAC (Poly Aluminim Chloride). The average amount of coagulant consumed was about 30,000 kg PAC/day. The sludge production was 115,800 kg/day in average over a year, which was collected from the operation data of the plant.

FDF : The electricity consumption was 740 kW/day. The coagulant consumption was 61 kg/day which was collected from the pilot-scale experiment carried out by Jung.[12] The sludge production was 593 kg/day which was calculated based on the removal of suspended solids and addition of coagulant in the pilot-plant.

3.2.3. Disposal Stage

CSF : When the CSF units were disposed, the major materials were usually classified as construction wastes because most of the materials were concrete. About 10% of construction wastes were disposed by landfill and 89% were recycled which was reported by the Korean government.[13] The landfill data were obtained from the Korean National LCI Database.[14] However the data for recycle and sludge disposal were obtained from the Ecoinvent (2003) and ETH-ESU 96 (2004), respectively.

FDF : The stainless steel was estimated to be recycled 100%. 50% of the flexible fiber was disposed to landfill and 50% was incinerated. For the recycle and sludge disposal above same databases were used in this case.

3.3. Life Cycle Impact Assessment (LCIA) and Interpretation

3.3.1. LCIA Depending on Life Cycle Stages

The analysis of the results was focused on the LCIA depending on the life cycle stages based on the Korean Eco-indicator as shown in the Fig. 3. Among three stages of the life cycle the operation stage affected most significantly in terms of the life cycle impacts, which were 95.58% and 55.37% for CSF and FDF, respectively. Their impacts at the construction stage were 1.69% and 38%, respectively. Likewise their environmental impacts at the disposal stage were 0.28% and 6.63%, respectively. The reason that the impact during operation stage especially in the CSF was so large, might be due to the longer period of operation than those of construction or disposal stage. The values in y axis are simply dimensionless index.

The negative value was found out at the disposal stage of CSF. This meant that there was an avoided impact, which reduced environmental impact due to recycling of construction waste. In case of FDF, the positive value appeared during the disposal stage because the impact due to the sludge disposal was higher than that due to the recycling.

The detailed data were not shown here but during the operation stage the impact of coagulants took 98.2% of whole impact in CSF and the impact of electricity took 47.2% of whole FDF impact. Therefore, to reduce environmental impact of those units the amounts of coagulant and electricity consumptions should be reduced respectively.

The results based on the Eco-indicator 99 which was shown

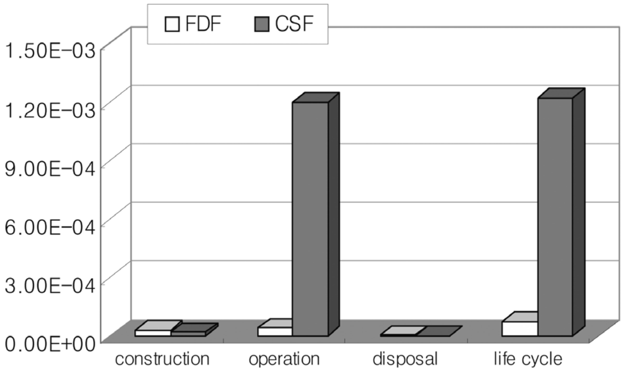

Fig. 3. LCIA depending on life cycle stages by Korean eco-indicator.

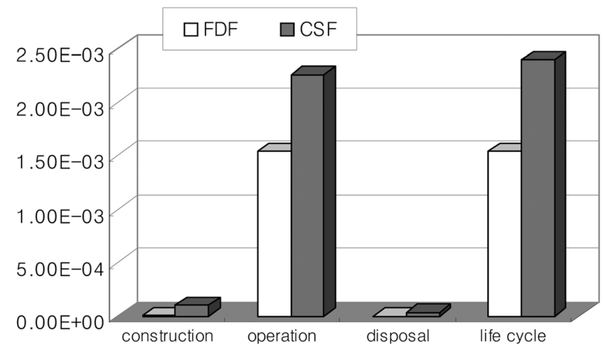

Fig. 4. LCIA depending on life cycle stages by Eco-indicator 99.

at the Fig. 4 were somewhat different but their trends were similar. The FDF impacts by the Eco-indicator 99 were appeared larger than those by the Korean Eco-indicator due to their different calculation principles.

3.3.2. LCIA Results on Impact Categories

As shown in the Fig. 5, the eco-toxicity was looked very serious in the CSF based on the Korean eco-indicator. The significant impacts on global warming and acidification were followed in CSF. In case of FDF, the impacts on global warming and human toxicity in order were significant. The major sources of the eco-toxicity were found to be hydrogen fluoride (67%) from the electric production and PAH (Poly Aromatic Hydrocarbon) (21%) from the steel pipe.

The Fig. 6 shows the results obtained based on the Eco-indicator 99. The impacts on fossil fuels, respiratory inorganic and climate change were very important in both systems. The major sources for fossil fuel were found to be crude oil (85%) and natural gas (14%).

Because the impact categories are different from between two LCIA methodologies, it is difficult to compare the results directly.

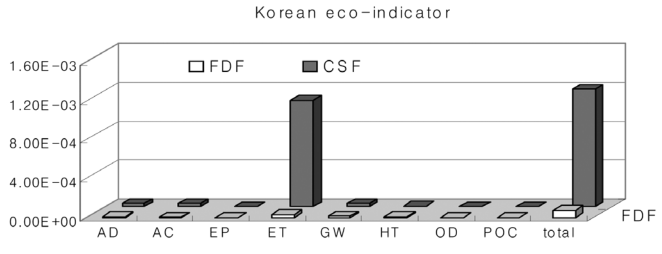

Fig. 5. The LCIA of Korean Eco-indicator.

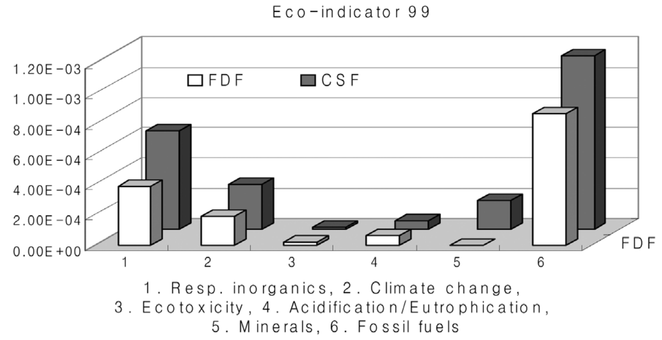

Fig. 6. The LCIA of eco-indicator 99.

3.3.3. Impacts Change Due to Replace CSF with FDF

The ISO14042 recommends that when one wants to compare two products, the evaluation should be done using only classification and characterization. It is because that the normalization and the weighting could interfere the results due to subjective factors.

In the Table 6 the results of characterization by LCIA based on the Korean Eco-indicator were shown by comparing those from the CSF and FDF. If the conventional CSF was replaced by the new FDF, the environmental impact would be changed also. These impact changes could be calculated by following equation. And the results were shown at the Fig. 7.

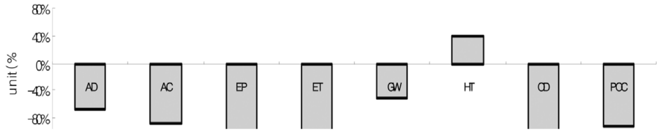

Fig. 7. The impact change of replacement with FDF.

impact change =

$$\frac{FDF(characterization\ equivalence) - CSF(characterization\ equivalence)}{CSF(characterization\ equivalence)}$$

The results obtained based on the Eco-indicator 99 were shown in the Table 7 and the Fig. 8, which were similar to those obtained based on the Korean Eco-indicator.

In most of the cases the results showed that the impact changes were negative. This meant that the impacts by the CSF would be reduced when it was replaced by the FDF. The impact on human toxicity or acidification/eutrophication was not reduced

Table 6. Comparative result of characterization using Korean Eco-indicator

	Unit	CSF	FDF
Abiotic resource depletion	1/yr	7.69E-04	2.48E-04
Acidification	kg SO2 eq	1.31E-03	1.58E-04
Eutrophication	kg PO4-3 eq.	6.30E+01	4.57E-01
Ecotoxicity	kg 1,4-DCB eq.	6.30E+01	4.57E-01
Global warming	kg CO2 eq.	1.84E-01	9.06E-02
Human toxicity	kg 1,4-DCB eq.	8.53E-03	1.18E-02
Ozone depletion	kg CFC-11 eq.	8.59E-08	1.57E-09
Photochemical oxidation	kg ethylen eq.	4.44E-05	3.15E-06

Table 7. The comparative result of characterization using Eco-indicator99

Impact category		Unit	CSF	FDF
Human health	Carcinogens	DALY	9.66E-10	1.89E-11
	Resp. organics	DALY	1.90E-10	1.24E-10
	Resp. inorganics	DALY	3.36E-08	1.99E-08
	Climate change	DALY	1.53E-08	9.90E-09
	Radiation	DALY	2.34E-15	5.01E-16
	Ozone layer	DALY	1.33E-12	3.06E-14
Ecology quality	Ecotoxicity	PAF*m2yr	2.22E-03	3.18E-04
	Acidification / Eutrophication	PDF*m2yr	7.93E-04	8.09E-04
	Land use	PDF*m2yr	1.51E-07	5.07E-08
Resource	Minerals	MJ surplus	0.00534	9.13E-05
	Fossil fuels	MJ surplus	3.23E-02	2.43E-02

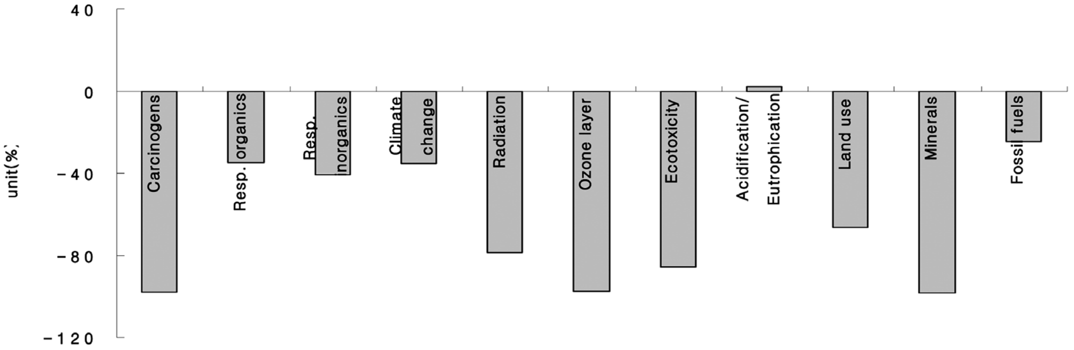

Fig. 8. The comparative result of characterization using Eco-indicator99.

which was assessed by the Korean Eco-indicator or Eco-indicator 99, respectively.

3.4. Comparison of LCIA Methodologies

Two LCIA methodologies, Korean Eco-indicator and Eco-indicator 99, were compared in this research. The trends of the results were somewhat similar but there were large differences in details as shown above figures. In fact these results were already expected to some degree because some principles and calculation procedures were quite different from each other.

In principle the difference of two methodologies lies on the different ways of approach to identify the environmental impacts caused by the inputs. The degree to identify the environmental impacts can be realized how much the physical, chemical or biological mechanisms can be quantified. Especially the category indicator at the classification and characterization steps can be calculated by different approaches such as a mid-point approach or an end-point approach.

The mid-point approach displays the category indicators as an environmental indexes such as global warming potential and ozone depletion potential. Therefore it shows very good environmental relationship. However there are too many indicators in this approach and it is difficult to analyze the results.

However the end-point approach is to show the quantified indexes developed by analysing the damages occurred on the safe guard subjects such as human health, eco-system, and natural resources. It is easy to analyze the results and there is relatively high confidence on that single index. The former was used in the Korean Eco-indicator, and the latter was adopted in the Eco-indicator 99.[10)]

Also the impact categories, characterization factors, normalization values and weighting factors were different from each other.[10)]

Therefore both methodologies have only a few same impact categories such as the ozone layer depletion, acidification, and eutrophication. As an example the comparison of ozone layer depletion was attempted. The Fig. 9 showed that the ozone dep-

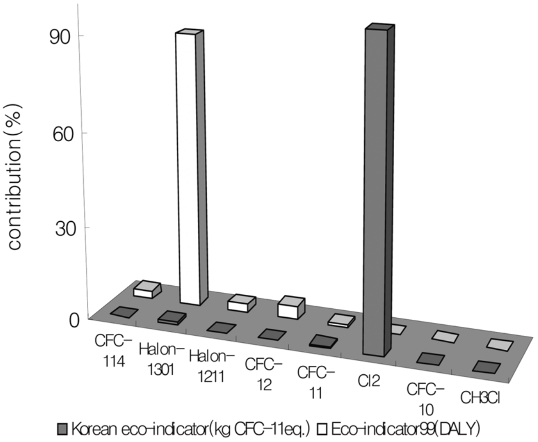

Fig. 9. The ozone layer depletion of two methodology.

letion in the FDF was caused by Halon-1301(88%), CFC-12(4.3%), and Halon-1211(2.7%) as key impact components which was analysed based on the Eco-indicator 99. When the Korean Eco-indicator was used the chlorine was the most important component which was even not appeared in the Eco-indicator 99. This was due to the fact that there was quite different sources adopted when the impact categories were developed during the classification step. The source for the Korean Eco-indicator was the data of material consumption for ozone depletion.9) But for the Eco-indicator 99 quite different another source was utilized.8)

Therefore one should be careful to perform comparison and should consider the geographical, cultural, and regional characters.

4. Conclusion

This study quantitatively identified environmental impacts of the new environmental technology called FDF and the existing CSF process on the life cycle of the water treatment plant. Both systems showed that there were significant environmental impacts during the operation stage. To reduce the environmental impacts the coagulants and electricity consumptions need to be cut down.

If the CSF was replaced with the FDF, the environmental impacts would be reduced in most of the impact categories except human toxicity or acidification/eutrophication which were evaluated based on the Korean Eco-indicator or the Eco-indicator 99, respectively. It can be concluded that the FDF would be better technology than the CSF in terms of life time environmental impacts.

The LCIA results of Korean Eco-indicator and Eco-indicator99 were very different from each other. These results were already expected because they were quite different from each other in terms of category indicators, impact categories, characterization factors, normalization values and weighting factors during their development. One should be cautious to choose the methodologies depending on their purposes.

This study showed that the life cycle assessment could be a valuable tool for evaluating the environmental impact of the new technology which was introduced in water treatment process.

Acknowledgements

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