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Life cycle impact assessment of the environmental infrastructures in operation phase: Case of an industrial waste incineration plant

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ABSTRACT

A life cycle impact assessment was applied in an industrial waste incineration plant to evaluate the direct and indirect environmental impacts based on toxicity and non-toxicity categories. The detailed life cycle inventory of material and energy inputs and emission outputs was compiled based on the realistic data collected from a local industrial waste incineration plant, and the Korean life cycle inventory and ecoinvent database. The functional unit was the treatment of 1 tonne of industrial waste by incineration and the system boundary included the incineration plant and landfilling of ash. The result on the variation of the impact by the unit processes showed that the direct impact was decreased by 79.3, 71.6, and 90.1% for the processes in a semi dry reactor, bag filter, and wet scrubber, respectively. Considering the final impact produced from stack, the toxicity categories comprised 91.7% of the total impact. Among the toxicity impact categories, the impact in the eco-toxicity category was most significant. A separate estimation of the impact due to direct and indirect emissions showed that the direct impact was 97.7% of the total impact. The steam recovered from the waste heat of the incineration plant resulted in a negative environmental burden

Keywords: Direct emission, Environmental impact, Incineration, Indirect emission, Industrial waste, Life cycle assessment

1. Introduction

In the past two decades, life cycle assessment (LCA) has been used as an important tool for assessing environmental impacts associated with a product throughout its entire life cycle, wherein the term ‘product’ refers to both goods and services. The LCA of a product is carried out by defining the goal and scope; by compiling an inventory of relevant inputs and outputs of the product system; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of inventory analysis and impact assessment phases in relation to the objectives of the study [1].

LCA, in general, is conceptualized to change the product use practices, to preserve resources, and to protect human and ecological health with a focus on sustainable development [2]. In this sense, application of LCA to infrastructure decisions appears to be of paramount importance. Till date, many LCA studies have been conducted about infrastructure construction [3-7], transportation system [8-10], wastewater treatment system [11-14], and waste treatment systems [15-19]. In these studies, LCA was used to evaluate the environmental performance of several infrastructures and compare various waste treatment options to determine the optimum waste management strategy (e.g., incineration, recycling and landfill) which have different performance characteristics. Usually, comparative assessment of various options is carried out early in the design of a product or process. On the other hand, if the design is finalized, or the product is in manufacture, or the process is in operation, LCA is carried out to achieve modest changes in environmental attributes at minimal cost or minimal disruption of the existing operation [20]. Anew, LCA of environmental infrastructures such as wastewater or waste treatment systems shows that the operation phase contributes to the environment impact significantly, while construction and demolition phases have a negligible environmental impact [13-14].

Environmental infrastructures are different from other infrastructure systems (Fig. 1) in a way that some pollutant ‘P’ enters to such infrastructures along with various other resources (e.g. chemicals and water) and energy (e.g. electricity and oil). In the output, pollutant P' (P' < P) is released along with wastes

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(e.g. ash, sludge, leachate) and products (e.g. steam, electricity, treated water, and biogas). Thus, LCA of environmental infrastructures require a lot of data starting from their construction to demolition phases. And, by ignoring the assessment of infrastructure construction and demolition phases, more specific assessment of operation phase is warranted to recognize the poorly performing unit processes and finding the opportunity to improve the environmental performance therein. Nevertheless, estimation of both direct and indirect emissions is required for an impartial evaluation of the total environmental impact resulting from such infrastructures. While direct emissions include air emissions from stack of waste incineration plants, greenhouse gas (GHG) emission landfills, and discharge of various contaminants from wastewater treatment plants (WWTPs), indirect emissions in the upstream originate from the production of energy, chemicals and other raw materials which are used in various unit processes of the environmental infrastructures.

Even the most technologically advanced incinerators emit thousands of pollutants that contaminate air, soil and water. Several identified emissions include heavy metals such as lead, cadmium, arsenic, chromium, and mercury, halogenated hydrocarbons, acid gases, particulate matter, and volatile organic compounds such as dioxin and furans [21, 22]. Toxics are created at various stages of such thermal technologies, and not only at the end of the stack. Waste incineration systems produce a wide variety of pollutants which are detrimental to human health. Such systems are expensive and does not eliminate or adequately control the toxic emissions from chemically complex municipal solid waste (MSW) [23].

Many researchers have studied to evaluate the environmental impact for incineration plant using LCA tool, but majority of the studies focused only on the reduction of carbon dioxide to evaluate waste-to-energy system. Even though toxic matter is an important issue in the incineration field, there are still limited studies in the aspect of dealing with toxic issues. In our previous study [24], we evaluated the environmental impacts of various unit operations of an industrial waste incineration plant by using the LCA tool. The impact categories considered in the evaluation were abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), and photochemical oxidation potential (POCP). However, the toxicity potential was not considered. As mentioned above, because waste incineration systems produce a wide variety of pollutants which are detrimental to human health, it is necessary to evaluate the environmental impact including toxicity categories for incineration system.

In order to evaluate the life cycle environmental performance during the operation phase, this study considers an industrial waste incineration plant as a case study. The paper mainly focuses on two objectives: (i) applying LCA methodology to evaluate environmental impacts of an incineration plant in the operation phase, considering both direct and indirect emissions and toxicity categories; (ii) study the contribution of each unit process of the incineration plant and compare the performance of the plant by adding steam recovery as an auxiliary function along with waste disposal.

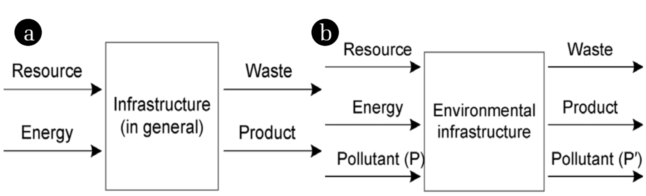

Fig. 1. Schematic diagram differentiating between a generalized infrastructure system (a), and an environmental infrastructure (b) with their inputs and outputs.

2. LCA of the Unit Process of an Incineration Plant

2.1. Incineration Plant and Various Processes Involved

In the incineration plant located in Ulsan industrial complex, solid wastes (2,200 kg/h) and liquid wastes (400 kg/h) are incinerated together with miscellaneous wastes (1,350 kg/h). The types of wastes and their physico-chemical characteristics are shown in Table 1.

Before incineration of the waste, pretreatment is done to remove the moisture by heating the industrial wastes (miscellaneous wastes only). The incineration of the waste in the grate comprises of feeding stage, drying stage, burning stage, and post-burning stage. The temperature in the incinerator is maintained in the range of 850°C - 1,050°C. A complete incineration of organic components in the flue gases is assured in the afterburner chamber through appropriate air intake, high

Table 1. Physico-chemical Characteristics of Industrial Wastes

Item	C	H	O	N	S	Cl	Ash	Moisture	Percentage in total waste
Solid waste (plastic, wood, and paper)	75.2	7.8	8.1	0.2	0.1	3.1	5.1	0.4	56
Liquid waste (oil and paint)	33.4	3.5	0.1	0.1	0.2	1.3	33.0	28.4	10
Miscellaneous (sewage sludge and food waste)	8.5	1.1	0.1	0.0	0.2	0.0	30.0	60.1	34

Note: Analyses are expressed in weight%.

temperature and a long holding time. The hot flue gases from the afterburner are cooled off in a boiler, prior to cleaning, which enable to recover the heat energy in the form of steam. Removal of pollutants from flue gas of the incineration plants, through filtration and absorption of pollutants, is generally carried out by dry, semi-dry and wet processes. Semi-dry process normally provides reasonably better performance with alkaline reagent (e.g. lime slurry) addition. In addition, when activated carbon is mixed with lime slurry, the process can efficiently capture dioxins and furans. The flue gases released from the incinerator are passed through the semi dry reactor (SDR), bag filter (BF), and induced draft fan (IDF) followed by wet scrubber (WS). The SDR is generally suitable for the removal of acidic gases such as HCl, HF, and SO_x from incinerator. This system injects an aqueous adsorbent like $Ca(OH)_2$ slurry, with higher sorbent concentration. As the hot flue gas is mixed with the aqueous sorbent, water is evaporated from the slurry. The water which remains on the solid adsorbent enhances the reaction with SO_2. Eventually, the process forms a dry waste product which is collected by a BF. The captured dust blown off from the base falls into a hopper, which is then evacuated by an appropriate device. Subsequently, the IDF exhausts the flue gas onto the WS. In this system, the flue gas is ducted to a spray tower where adsorbent slurry is injected into the flue gas. The WS removes the acidic constituents (HF, HCl and H_2SO_4) present in the flue gas. Moisture present in the slurry is partially removed which results in the saturation of the waste gas stream. The SO_2 dissolves into the slurry droplets, thereby reacting with the alkaline particulates. The wastewater generated from some of the processes is disposed to the ash pit and is allowed for natural evaporation. Steam (8.5 kgf/cm^2, 180°C) is generated in the waste heat boiler at an average of 4,694 tonnes/mon, with a minimum of 2,388 tonnes/mon and a maximum of 6,197 tonnes/mon.

2.2. Goal and Scope Definition

The goal of this study is to evaluate the environmental impact contributed by each unit process during the incineration plant operation. Fig. 2 shows inputs and outputs in seven unit processes in the incineration plant: Pretreatment, incinerator, boiler, SDR, BF, IDF, and WS.

Based on the functional unit of 1 tonne of industrial waste incineration, the input data related to raw materials, ancillary materials, utility, ash landfilling, steam recovery, and emission to air were collected and calculated (Table 2). The mass balance calculation for each process was based on the incineration plant design information and CO_2 emission was calculated based on the elemental analysis of the incinerated wastes [25]. The emission of other air pollutants (such as CO, NO_x and SO_x) was measured from the stack for 5 d and its average values were used for this study. The emission of CO_2, CH_4 and N_2O resulted due to the use of diesel while heating up the incinerator was calculated based on the manufacture and industry emission factors [26]. And the other emissions such as NO_x and SO_x were calculated based on the emission factors from Korea Energy Management Corporation (KEMCO) [27].

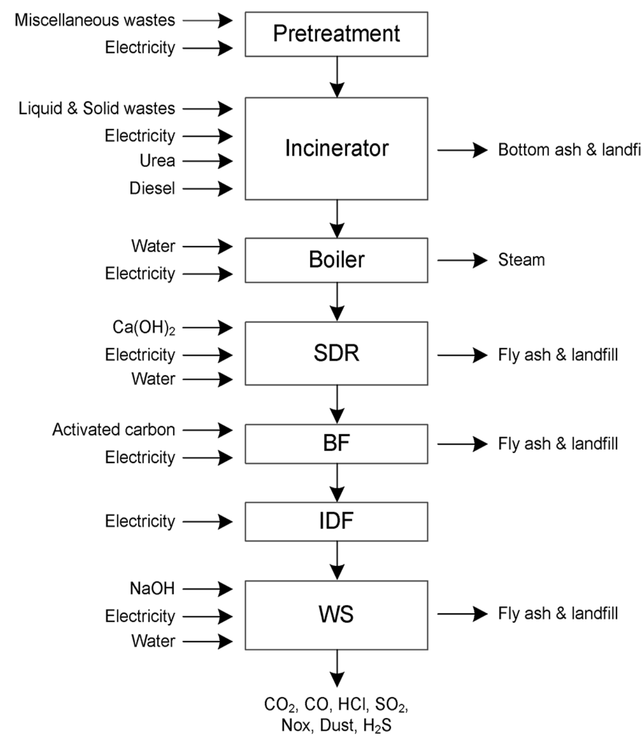

Fig. 2. Inputs and outputs for 1 ton of industrial waste incineration (SDR: Semi-Dry Reactor, BF: Bag Filter, IDF: Induced Draft Fan, WS: Wet Scrubber).

In the company to operate the subject incineration plant, there was no data about the removal of pollutants in the unit processes. This study calculated the removal of pollutants such as HCl, SO_x, NO_x, CO, HF, HCN, H_2S, NH_3, HCHO, and heavy metals such as lead, copper, zinc and chromium based on their removal efficiency in waste incineration facilities [28, 29]. This study evaluated the variation of the environmental impact by the unit processes by considering that the removal of gaseous air emissions in SDR and WS process is 90%, and that of particulate air emissions in BF and WS process is 90%. Meanwhile, the impact variation for dioxin by the unit processes is not considered in this study due to lack of data on the generation and removal efficiency of dioxin in each unit process. However, the company operating the incineration plant has the data on the final emission concentration of dioxin from the stack and the dioxin emission in the stack is included in direct emission.

2.3. Life Cycle Inventory Analysis and Impact Assessment

Table 2 shows input and output data pertaining to raw materials, ancillary materials and utilities (water, bunker-C oil and electricity), emission to air and wastes/products. Based on this data, a life cycle inventory (LCI) of gate-to-grave material inputs and emissions were compiled using Korean LCI database (KEITI) [30]. The LCI database of Ministry of Environment (MOE) was used for industrial water, NaOH (caustic soda), $Ca(OH)_2$, and activated carbon. Similarly for diesel, electricity, and steam,

Table 2. Input and Output in Each Waste Incineration Process

		Item	Unit	Pretreatment	Incinerator	Boiler	SDR	BF	IDF	WS
Input	Raw materials	Liquid waste	ton	1.025						
		Drum waste	ton		0.101					
		Solid waste	ton		0.557					
	Ancillary materials	Urea	kg		2.8					
		$Ca(OH)_2$	kg				37.3			
		NaOH	kg							6.1
		Activated carbon	kg					0.82		
	Utility	Water	kg			1,650	149			901
		Diesel	kg		0.105					
		Electricity	kWh	43.4	40.8	9.6	10.4	10.1	33	8.2
Output	Wastes/ Products	Ash	kg		140		35	61		15
		Steam	MJ			4,539				

Source: Yoosung Corp. Ltd.

the LCI database provided by Ministry of Trade, Industry and Energy (MOTIE) was used while that for urea and ash landfill, Ecoinvent LCI database [31] was used.

The resulting LCI details for each incineration unit process are summarized in Table 3. The impact categories considered in the evaluation are ADP, AP, EP, GWP, ODP, POCP, human toxicity potential (HTP), and eco-toxicity potential (ETP). The life cycle impact assessment (LCIA) methodology in this study is based on the Korean eco-indicator [32], which has been modified to suit Korea's industrial situation with Eco-indicator 95 method [33-35]. This LCIA methodology was used to assess and compare the environmental impact in each unit process of the incineration plant. Transport has a minor impact in the total emissions, when comparing with other phase [36-38]. Therefore, this study has excluded the environmental impact from the transportation phase for chemicals and ash landfilling.

3. Results and Discussion

3.1. Environmental Impacts of Unit Processes in the Incineration Plant

The change in environmental impact due to direct and indirect emission by the gradual addition of unit processes is shown in Fig. 3. The environmental impact due to direct emission was noticeably decreased, especially after the addition of SDR. In the boiler process, the impact due to direct emission was visibly decreased because there is no ash landfilling. And in the BF process, the impact due to direct emission was marginally increased because of ash landfilling. Meanwhile, the impact due to indirect emission was slightly increased. Though it appears that there is a marginal decrease in environmental impact due to direct emission after the addition of BF, IDF and WS, the reduction in this category in the real world situation cannot be ruled out. This is because BFs have the ability to efficiently capture (more than 90%) dioxins, which usually poses significant toxicity and can have severe environmental impact. Nevertheless, accurate estimation was not possible due to lack of data/information. The higher impact due to indirect emission as observed in SDR, BF and WS was mainly contributed by the energy and raw material consumption. Therefore it is clear that underestimation of impact due to indirect emission can result in biased conclusion. Though addition of the unit processes is essential to meet the air quality control guideline, careful estimation of overall impact (both in the downstream as well as in the upstream) is highly required.

This part of the study considered waste disposal as the incinerator's sole function and explained the total environmental impact due to direct and indirect emissions associated with each process. In this part, we considered the final environmental impact produced from the stack. The environmental impact due to air emissions emitted from the stack was considered to be the impact of the incineration process. That is because of the air emissions emitted from stack is produced by the incineration process. The characterization results showed the ADP to be 0.621 y^{-1} of waste incineration. With regard to ADP, contributions of SDR, incinerator, and pretreatment were 49%, 15% and 12%, respectively, and the highest contribution of SDR in this category was entirely due to indirect emission (Fig. 4(a)). This is because SDR process consumes significant amount of raw material and energy including electricity, $Ca(OH)_2$, and water. Besides, the ash discharged from this process also requires energy for its disposal in the landfill site. In this process, the effect of $Ca(OH)_2$ that was used to remove acidified gases was the highest (88%). The estimated AP of 1.66 kg SO_2-eq. was mainly contributed by the incinerator (68%), SDR (11%) and pretreatment (6%) processes. Air emission from the incinerator resulted in AP of 1.0 kg of SO_2-eq. and disposal of ash to landfill resulted in 0.1 kg SO_2-eq. With a total of 2.32 kg PO_4^{3-}-eq. of waste incineration in the EP category, the contribution of the incinerator and BF were 57% and 23%, respectively. The GWP was 1,970 kg CO_2-eq. due to waste incineration, of which the contribution of CO_2 was 93.4%. In an earlier study on MSW incineration,

Table 3. Summarized Results of Inventory Analysis for Each Process

	Inventory parameter	Unit	Pre-treatment	Incinerator	Boiler	SDR	Bag Filter	ID Fan	Wet scrubber
I	(r) Coal	kg	7.62E+00	1.15E+01	1.74E+00	2.57E+00	3.06E+00	5.80E+00	2.84E+00
I	(r) Natural gas	kg	9.77E-01	9.24E-01	2.28E-01	1.52E+01	2.27E-01	7.43E-01	1.15E+00
I	(r) Crude oil	kg	9.44E-01	9.95E-01	2.19E-01	1.47E+00	2.20E-01	7.18E-01	8.44E-01
I	(r) Water	kg	9.01E-01	8.63E-01	1.70E+03	1.54E+02	2.10E-01	6.85E-01	9.62E+02
I	(r) Limestone	kg	1.97E-05	0.00E+00	1.66E-04	4.91E-04	0.00E+00	1.50E-05	5.12E-04
I	(r) Iron ore (46%)	kg	0.00E+00	1.23E+01	1.24E-05	2.94E+00	5.12E+00	0.00E+00	1.26E+00
I	(r) Sodium chloride	kg	6.19E-04	7.37E-01	1.03E-03	1.89E-01	3.14E-01	4.70E-04	3.78E+00
I	(r) Clay	kg	7.72E-06	1.92E-01	1.71E-06	4.61E-02	8.03E-02	5.87E-06	1.97E-02
I	(r) Aluminium	kg	0.00E+00	1.44E-01	0.00E+00	3.23E-02	5.62E-02	0.00E+00	1.38E-02
I	(r) Zinc - copper ore (4.07%-2.59%)	kg	0.00E+00	4.30E-02	0.00E+00	9.53E-03	1.66E-02	0.00E+00	4.09E-03
I	(r) Dolomite	kg	0.00E+00	2.59E-02	1.03E-07	6.19E-03	1.07E-02	0.00E+00	6.13E-03
I	(r) Kaolinite	kg	0.00E+00	2.03E-03	5.84E-08	4.98E-04	8.67E-04	0.00E+00	2.14E-04
I	(r) Sand	kg	2.92E-07	1.19E-03	2.09E-06	2.94E-04	5.12E-04	2.22E-07	4.40E-02
I	(r) Sulfur	kg	0.00E+00	1.14E-03	3.47E-03	5.98E-04	4.93E-04	0.00E+00	2.12E-03
I	(r) Lead	kg	0.00E+00	3.39E-04	5.04E-09	0.00E+00	1.08E-04	0.00E+00	3.16E-05
I	(r) Caliche	kg	3.05E-04	2.86E-04	6.97E-05	7.32E-05	7.09E-05	2.32E-04	1.01E-04
I	(r) Wood	kg	1.08E-07	5.37E-04	2.48E-08	1.82E+02	2.19E-04	8.24E-08	5.39E-05
O	(a) CO_2, fossil	kg	2.11E+01	1.84E+03	4.84E+00	3.56E+01	2.54E+01	1.61E+01	1.27E+01
O	(a) Sulfur dioxide	kg	7.07E-02	4.19E-01	1.56E-02	2.55E-02	3.91E-02	5.38E-02	2.11E-02
O	(a) Nitrogen oxides	kg	5.18E-02	8.72E-01	1.19E-02	2.28E-01	5.76E-02	3.94E-02	3.27E-02
O	(a) Hydrocarbons	kg	4.37E-02	4.11E-02	1.00E-02	1.35E-02	1.03E-02	3.32E-02	1.45E-02
O	(a) Methane, fossil	kg	1.53E-02	3.69E-02	3.51E-03	2.17E-02	4.39E-03	1.17E-02	6.49E-03
O	(a) CO, fossil	kg	2.10E-03	3.72E-01	4.86E-04	1.28E-02	2.29E-02	1.60E-03	6.00E-03
O	(a) Ammonia	kg	4.86E-05	1.06E-02	1.11E-05	3.98E-04	6.66E-04	3.70E-05	1.77E-04
O	(a) Acetaldehyde	kg	6.63E-06	4.13E-05	1.52E-06	9.78E-06	1.50E-05	5.04E-06	5.52E-06
O	(a) Zinc	kg	4.60E-06	3.07E-03	1.05E-06	1.91E-06	1.82E-06	3.50E-06	1.71E-06
O	(a) Hydrogen chloride	kg	2.06E-07	6.76E-02	1.25E-07	1.22E-04	1.84E-04	1.57E-07	4.68E-05
O	(a) Hydrogen fluoride	kg	2.01E-07	1.73E-02	1.57E-06	2.30E-05	9.24E-06	1.53E-07	3.10E-05
O	(a) Phenol	kg	7.46E-08	6.93E-07	1.71E-08	1.13E-07	1.74E-07	5.68E-08	6.37E-08
O	(a) Chlorine	kg	9.03E-09	2.46E-06	2.16E-09	1.08E-07	1.85E-07	6.86E-09	2.89E-07
O	(a) Nickel	kg	3.67E-09	2.04E-05	8.40E-10	1.22E-06	1.99E-06	2.79E-09	5.58E-07
O	(a) Benzene	kg	2.64E-09	7.90E-05	6.05E-10	9.82E-06	1.54E-05	2.01E-09	3.85E-06
O	(a) Lead	kg	3.66E-10	1.41E-03	8.37E-11	1.76E-07	2.30E-07	2.78E-10	6.35E-08
O	(a) Cadmium	kg	1.51E-10	1.13E-06	3.46E-11	1.52E-08	2.09E-08	1.15E-10	8.59E-09
O	(a) Manganese	kg	5.64E-11	1.12E-06	1.29E-11	1.56E-07	2.73E-07	4.29E-11	6.71E-08
O	(a) Halon 1301	kg	4.95E-11	2.02E-07	1.09E-11	7.31E-08	1.11E-07	3.76E-11	1.93E-08
O	(a) Mercury	kg	2.50E-11	4.04E-07	5.73E-12	2.54E-08	3.03E-08	1.90E-11	8.09E-09
	(w) Dissolved solids	kg	1.37E-01	1.29E-01	3.13E-02	4.24E-02	3.22E-02	1.04E-01	4.54E-02

I - input; O - output; (r) - resources; (a) - air emissions; (w) - water emissions

the major cause of climate change was demonstrated as CO_2 emission [39]. The POCP was 0.049 kg C_2H_4-eq. of waste incineration in which the incinerator contributed to 74% of the total impact.

The HTP and ETP were 131.2 kg 1,4 DCB-eq. and 1,490 kg 1,4 DCB-eq. of waste incineration, respectively, in which the contributions of incinerator and BF were 59%, 56% and 22%, 24%,

Table 4. Weighting Results

Process \ Category	ADP	AP	EP	GWP	ODP	POCP	HTP	ETP	Total
Pretreatment	4.82.E-05	1.21.E-04	4.56.E-05	8.00.E-04	3.11.E-08	2.26.E-05	9.82.E-05	4.04.E-06	1.14.E-03
Incinerator	6.02.E-05	1.29.E-03	8.86.E-03	6.90.E-02	1.36.E-05	2.32.E-04	1.22.E-01	4.56.E-01	6.57.E-01
Boiler	1.11.E-05	2.72.E-05	1.04.E-05	1.83.E-04	7.44.E-09	5.01.E-06	2.27.E-05	9.42.E-07	2.61.E-04
SDR	1.94.E-04	2.11.E-04	2.22.E-03	1.36.E-03	1.97.E-06	1.12.E-05	2.71.E-02	1.12.E-01	1.43.E-01
Bag filter	1.50.E-05	9.17.E-05	3.56.E-03	9.71.E-04	3.02.E-06	1.67.E-05	4.52.E-02	1.95.E-01	2.45.E-01
ID fan	3.66.E-05	9.24.E-05	3.46.E-05	6.09.E-04	2.37.E-08	1.72.E-05	7.46.E-05	3.07.E-06	8.67.E-04
Wet scrubber	3.44.E-05	5.04.E-05	8.93.E-04	4.89.E-04	1.39.E-06	7.93.E-06	1.21.E-02	4.81.E-02	6.18.E-02
Total	4.00.E-04	1.88.E-03	1.56.E-02	7.34.E-02	2.01.E-05	3.13.E-04	2.06.E-01	8.11.E-01	1.11.E+00

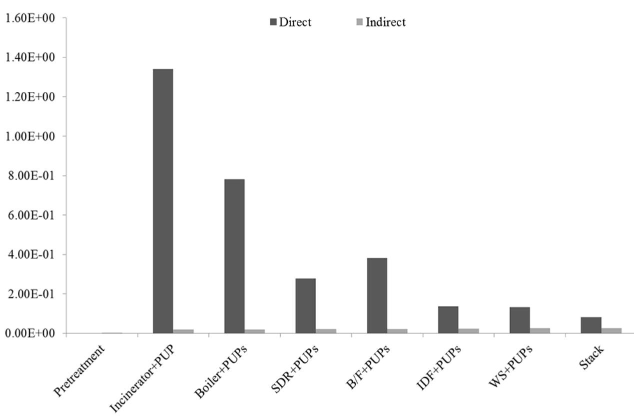

Fig. 3. Change in environmental impact due to direct and indirect emissions by addition of unit processes (PUP: Previous unit process).

respectively. Landfilling of ash contributed significantly to the HTP (92%) and ETP (99%) categories. Fruergaard et al. [40] have demonstrated similar result due to landfilling of air pollution control residues (fly ash or bottom ash) on HTP and ETP categories. The contribution of incinerators to HTP and ETP categories has also been described elsewhere [41]. According to data on the final emission concentration of dioxin, a nanogram level of dioxin is emitted at the final stage. By considering this dioxin concentration, the HTP and ETP of waste incineration were increased by 4.95 kg 1,4 DCB-eq. (126.21 kg 1,4 DCB-eq. → 131.16 kg 1,4 DCB-eq.) and 0.76 kg 1,4 DCB-eq. (1,488.87 kg 1,4 DCB-eq. → 1,489.63 kg 1,4 DCB-eq.), respectively. The dioxin's characterization factors to HTP and ETP are high, but the emitted dioxin quantity is too low in terms of the nanogram level. The impact by dioxin is therefore insignificant. In this study, the impact due to dioxin is only considered to be minor.

The environmental impact due to direct emission was predominant as 97.7%, but the indirect emission was only minor at 2.3%. The indirect emission was 2.4% of the direct emission (Fig. 4(b)). The significant contribution of direct emission is attributed to the landfilling of ash, while the indirect emission is attributed to the use of electricity and urea. Other than ADP and ODP categories, the environmental impact of incinerator was mainly due to the direct emission (Fig. 4(a)). The ODP was 9.64E-06 kg CFC 11-eq. of waste incineration, of which the incinerator contributed to as high as 68%, mainly due to the indirect emission as a result of urea consumption and the direct emission as a result of ash landfilling.

There are different units for environmental impact categories in the characterization results. But through the normalization and weighting steps, the environmental impact can be compared with each category. The normalization and weighting factors used in this study were adopted from Korean eco-indicator [32, 33]. Table 4 shows the weighted environmental impact of each unit process in the incineration plant. Among the processes, incinerator had the most environmental impact (59%) and BF had 22% of total environmental impact. Eco-toxicity stands out as the impact category with highest damage score (73%), followed by human toxicity (19%).

Comparing non-toxicity impact categories (ADP, AP, EP, ODP, GWP, and POCP) and toxicity related impact categories (ETP and HTP), toxicity related impact is dominant at 91.7% while non-toxicity impact is insignificant at 8.3% [Fig. 5]. This result indicated that the toxicity should be considered in the evaluation of the environmental impact for incineration. Meanwhile, according to our previous study [24], the incinerator had the highest environmental impact at 87% and SDR had the second highest impact at 5% among other processes. GWP accounted the highest impact score (more than 85%), followed by eutrophication (6%) among the various categories of environmental impact. Quantitative direct and indirect impacts were 89% and 11%, respectively. Considering toxicity categories, the impact of the incinerator was decreased, and the impacts of toxicity categories were the first (ETP) and second (HTP) highest. The impact due to direct emission was also increased from 89% to 98%.

3.2. Avoided Impact Due to Steam Recovery

Energy recovery, in the past, has led to the introduction of a typical LCA concept. The environmental impact or damage through the energy gained (in terms of thermal or electric energy) due to waste incineration avoid the consumption of fossil fuels and reduce the emission of pollutants for an equivalent amount of energy (avoided environmental impact) [42].

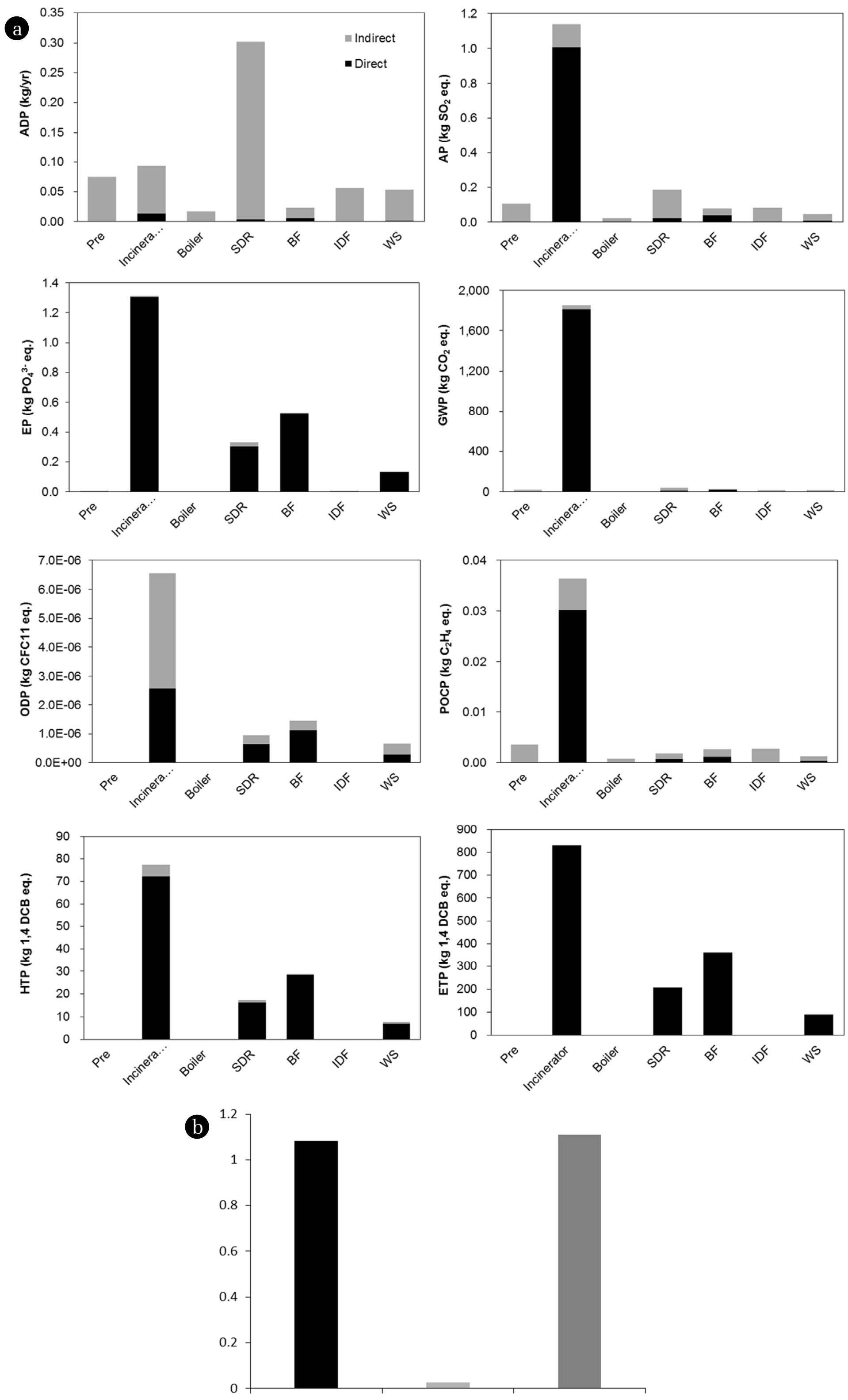

Fig. 4. Valuation of total environmental impacts in each process with respect to various impact categories (Pre: Pretreatment, SDR: Semi-Dry Reactor, BF: Bag Filter, IDF: Induced Draft Fan, WS: Wet Scrubber).

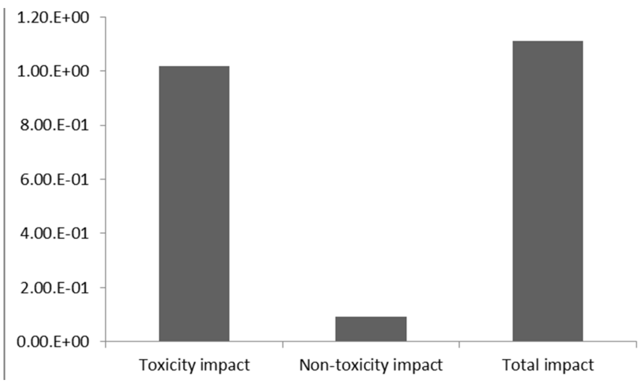

Fig. 5. Valuation of non-toxicity impact and toxicity impact.

In this section, steam recovery from the waste heat of an industrial waste incinerator was evaluated, i.e. the incinerator was studied for waste disposal as well as energy recovery functions. Presently, there exists a steam network between the incineration plant under discussion and a nearby paper mill. The steam produced in the boiler using waste heat obtained from the incinerator can reduce emissions that would have otherwise been produced by other energy systems using fossil energy vectors. Recently, energy recovery including steam has been considered as a necessary condition for new generation incineration plants for which these two functions should be considered together [43, 44]. The results shown in Fig. 6 have both positive and negative value: positive value means a positive environmental impact and, as a consequence there is damage at the environmental level. On the contrary, negative value means a negative environmental impact, which is equivalent to an avoided burden. From the life cycle view point, the incineration plant with steam production is able to assure greater avoided impacts for the categories ADP, AP, ODP, POCP, and HTP. Referring to ADP category, environmental impact due to incineration was 0.62 kg/y and the avoided impact was 2.61 kg/y (Fig. 6(a)). Therefore, the net environmental impact was -1.98 kg/y. In the case of GWP category, the environmental impact of incineration was 1,970 kg CO_2-eq. and the avoided impact due to steam production was 484 kg CO_2-eq. with a net impact of 1,486 kg CO_2-eq. (about 25% reduction of total GWP). Similarly, in terms of EP and ETP categories, the environmental impact of incineration was 2.32 kg PO_4^{3-}-eq. and 1,490 kg 1,4 DCB-eq. and the avoided impact was 0.16 kg PO_4^{3-}-eq. and 512 kg 1,4 DCB-eq., respectively with a net impact of 2.16 kg PO_4^{3-}-eq. and 977 kg 1,4 DCB-eq. Even though there was no avoided burden in the GWP, EP and ETP categories, the overall impact due to steam recovery resulted in negative environmental impact (Fig. 6(b)). In the ‘no energy recovery’ scenario (incineration only), a net environmental impact is observed, as the incineration system is not credited with any avoided emissions. But, as soon as there was energy (steam) recovery, five of the eight impact categories showed an overall saving.

It must be kept in mind that the type of fuel substituted (Bunker-C oil) can have as much influence as that of the energy recovery from the incinerator and also that of substituted energy source (e.g., electricity, steam, etc.). Incineration of MSW, with energy recovery as the auxiliary function, allows for production of electricity by exploiting the heat of flue gases. This has shown to compensate the environmental damages by avoiding the use of energy obtained from fossil fuel exploitation [45]. It has also been reported that greenhouse gas emission due to MSW incineration was reduced by 14.6% as a consequence of avoided electricity production from conventional power production [46].

3.3. Implication of the Result

LCA of the incineration plant showed that steam recovery from waste heat has resulted in the negative environmental impact. However, consideration of the economic aspects of putting the results into practice is beyond the scope of this analysis. One way of using the produced steam in the incineration plant was its supply through a steam network. The efficiency of steam and electricity co-generation is 62% [47], which indicates that the efficiency of steam production alone from waste heat could be higher (> 70%). This value is quite higher than the efficiency of electricity production (35%) from waste heat [47]. Therefore, from the view point of industrial requirement, steam production was encouraged from the waste heat of the incinerators present in the industrial complexes. The incineration plant is supplying 10 steam tonne/h to the paper mill. The paper mill is economically benefitted in terms of its relaxation from the taxes levied on it for consuming fossil fuel (bunker-C oil), which was conventionally used for steam production. On the other hand, waste incineration plant, as the supplier of steam; derive revenue from receiving the waste from other companies as well as selling steam to the paper mill. For instance, the incineration plant and the paper mill share an annual profit of 2.32 million US$/y while reducing 19,058 tonne CO_2/y and 135 tonne/y of other air pollutants including SO_x, NO_x, CO, etc. [48]. Comparing the situation when the plants operated in isolation, the utilization of waste heat from incineration plant introduces both economic and environmental benefits and, maximizing energy recovery by waste incineration was desirable. In a similar view point, the methodology applied in this study can be adopted to other types of environmental infrastructures such as wastewater treatment facilities or landfills wherein the reuse of wastewater effluents or recovered biogas can play the same role of avoidance as that observed in this study in the form of steam recovery from waste heat.

Stringent environmental regulations imposed in the recent days put tremendous pressure on various environmental infrastructures to drastically reduce the pollutant emissions. Eventually, it results in the addition of more unit processes to the existing infrastructures. However, inclusion of additional unit processes for better environmental quality warrants a comprehensive life-cycle understanding of the performance of various processes in such facilities. This shall not only help in assessing the impacts of the various individual unit processes but also help to get the feedback on improving the operational efficiency of these processes minimizing the overall environmental impact. As evident from this study, the location of incinerators should not only consider impacts due to direct emission. It should also consider impact due to indirect emission as well as avoided

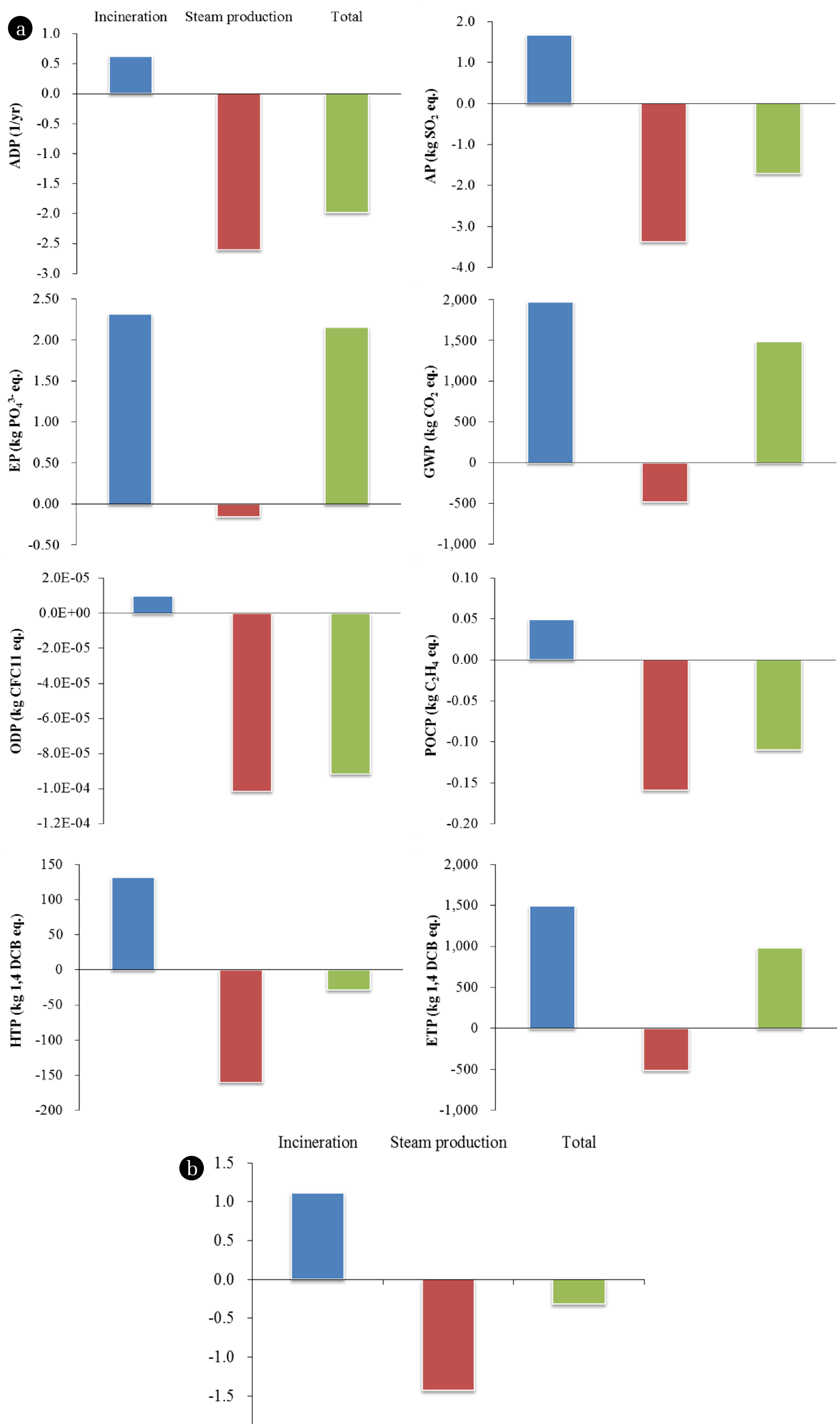

Fig. 6. Change in environmental impact due to the steam recovery.

impacts, if any, to aid in decision making processes. The regulations pertaining to the location of waste incinerators within industrial complexes should take into account the synergistic effect of benefits resulting out of sharing or exchange of wastes or energies.

4. Conclusions

The methodology adopted in this study can be applied to different kinds of environmental infrastructures in order to evaluate their performance. In this study, LCA is focused on the operational phase of the incineration plant, primarily due to the higher environmental impact incurred in this stage as compared to the construction and demolition phases. As a whole, results on the variation of the environmental impact by the unit processes showed that the direct impact were decreased by 79.3%, 71.6%, and 90.1% by the SDR, BF and WS processes, respectively. In the BF process, the impact due to direct emission was increased by ash landfilling. In consideration to the final environmental impact produced from the stack, the toxicity impact categories like ETP and HTP were predominant at 91.7% of the total impact. In the toxicity impact categories, the environmental impact in the ETP category was found to be most significant. Separate estimation of impacts pertaining to direct and indirect emissions showed that of the impact due to direct emissions is 97.7% of the total impact. This result demonstrated that the environmental impacts due to the direct emission should be highly considered before the establishment of incinerators in a city or a region and should be supported by the policy decisions. Meanwhile, the impact due to direct emission could reduce to control air pollutants through air emission control processes. And because the use of electricity and urea is the main contribution for indirect emission, the impact due to indirect emission could be reduced by minimizing electricity consumption through the utilization of renewable energy and the heat generated by the incineration process and by substituting urea to an alternate material in order to remove NO_x. The significant environmental impact reduction owing to steam recovery indicated that the industrial complexes, with the requirement for very high quantity of energy, may consider using steam recovered from waste incineration plants. The study, limited to the assessment of the incineration process performances, can be extended for performing a most detailed analysis considering the impact due to dioxin emission and the release of many other heavy metals.

Acknowledgements

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