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An impact analysis of landfill for waste disposal on climate change: Case study of 'Sudokwon Landfill Site 2nd Landfill' in Korea

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Abstract−The impact of waste landfill on climate change was analyzed by comparing the amount of CH_4 emission from landfill with the potential energy conversion. For this analysis, compulsive collection and surface emission amount of CH_4 were used against Sudokwon Landfill Site 2nd Landfill, which is currently under operation in the Republic of Korea. As a result of the estimation, the total CH_4 amount which can be collected from the Sudokwon Landfill Site 2nd Landfill during 2001-2035 is $3,068\times10^6$ N m^3. During the same period, the total CH_4 emission amount from the landfill slope, intermediate covering and final covering is 899×10^6 N m^3. Especially, 95% (854×10^6 N m^3) of the total surface emission is emitted during the landfill period 2001-2015. After final covering, in the period of 2016-2035, only 5.0% (45×10^6 N m^3) is emitted. Additionally, as a result of analysis by comparing the surface emission amount from the route of the slope, intermediate covering and final covering, 92.8% (834×10^6 N m^3) of CH_4 is emitted from intermediate covering during landfill operation. The CH_4 emission from the surface of Sudokwon Landfill Site 2nd Landfill during 2001-2035 can be converted to 32.9×10^6 Ton in CO_2 bases. On the other hand, on CO_2 bases, the reduction amount of global warming gas by converting compulsorily collected CH_4 to energy source is about 19-33% of surface emitted CH_4. It can be concluded that to improve the landfill method as a waste treatment methodology which can better adapt to the climate changes, various research and development on the intermediate covering system along with the fundamental enhancement on present landfill facility establishment standards and operating guidelines are required.

Key words: CH_4, Landfill Covering, Surface Emission, Fossil Fuel, Climate Change

INTRODUCTION

Recently, projects to utilize CH_4 from landfill sites as a energy source are actively being carried forward [1-3]. It indicates that the role of the landfills is shifting from the final waste treatment site to energy production facilities. However, the surface emission of CH_4 from landfill sites is inevitable; thus the impact on climate change cannot be neglected. From environmental and economic point of view, besides the running and capital cost and energy selling benefits, other adverse effects, especially that of CH_4, must be considered [4]. Consequently, though the benefits of reducing the impact on the climate change can be expected from fossil fuels replacement by CH_4 from landfills as energy source, it is indispensable to analyze the relative effectiveness compared to the surface emission impact. Also, the differences of emissions from slope, intermediate covering and the final covering must be considered as an important factor in landfill site management.

This research estimates the potential amount of CH_4 which can be used as an energy source and surface emission from the Sudokwon Landfill Site 2nd Landfill in Republic of Korea. Furthermore, this research intends to evaluate fossil fuel replacement effects and the impact on climate change while investigating the improvements in landfill site designs and operations.

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METHODOLOGY

1. LFG Estimation

The research site, Sudokwon Landfill Site, handles approximately 37% of waste generated in the Republic of Korea [5]. The 1st Landfill of Sudokwon Landfill Site was in commission during 1992-2000. In the 2nd Landfill, $56,070\times10^3$ tons of waste have been disposed since October of 2000. The 2nd Landfill was designed with the total of 8 layers and 25 blocks. Among the 25 blocks only 3 blocks are operating as daily disposing area to reduce environmental impacts, and other blocks are maintained as intermediately covered status until the disposing time. The analysis period is set to 35 years, from 2001 to 2035 where the first year of CH_4 emission is 2001 and the site decommission is planned in 2015. Location and structure design information of Sudokwon Landfill Site 2nd Landfill are shown in Fig. 1 and Table 1.

The constitutional analyzed data of disposing was used for the time period of 2000-2010 [6]. For data in the period of 2011-2015, trends analysis was performed for the estimation [7-9]. First-order decay model was used for CH_4 model [10,11]. L is maximum CH_4 formation potential, W is the waste amount disposed per year and k refers to the rate of CH_4 generation.

$$Q_{CH_4}=\sum_{i=1}^{n}\sum_{j=1}^{m}L_i\cdot W_{ij}\cdot(1-e^{-k_j\cdot(t-j+1)}) \quad (1)$$

Q_{CH_4} : Accumulated CH_4 by time elapsed (N m^3)

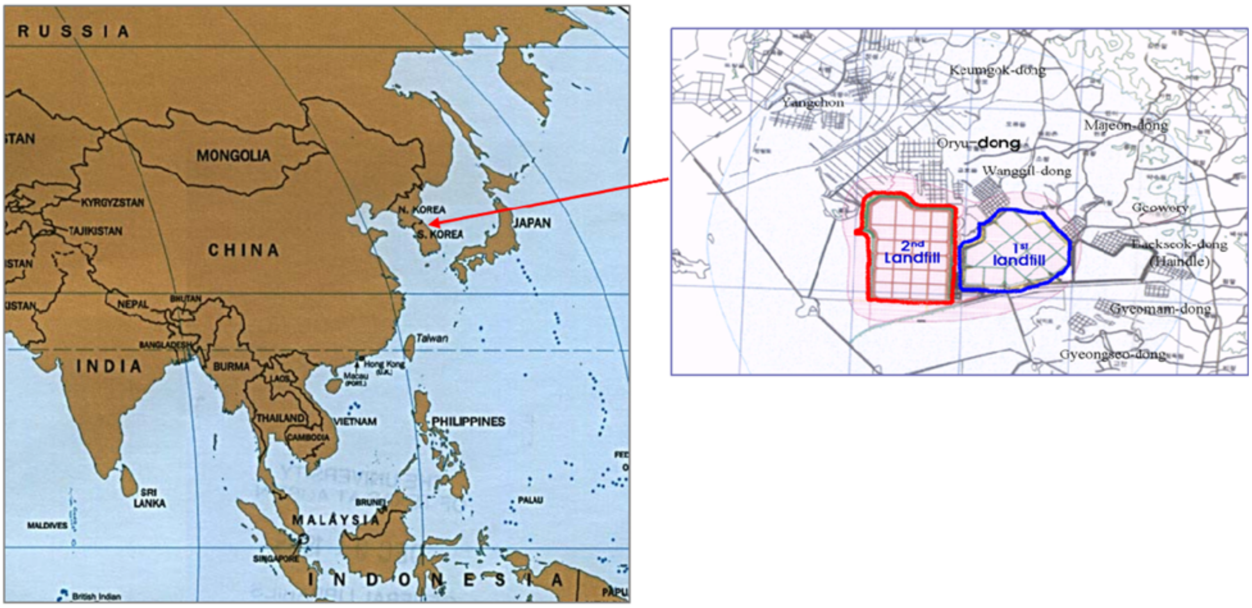

Fig. 1. Location of Sudokwon Landfill Site 2nd Landfill.

Table 1. Design structure and operating standards for Sudokwon Landfill Site 2nd Landfill

General	Total area	2,461,767 m^2
	Block number	25
	Block size (aver.)	300 m×300 m
Structure	Waste layer	4.5 m
	Intermediate covering	0.5 m
	Total height	(4.5+0.5)×8=40 m
	8 layer (waste and middle covering)	
Slope	Stepped distance length	22-29 m
Final covering	Gas venting layer, Low permeability layer, Drainage layer, Vegetation (soil top) layer, Gradient 2%	

L : CH_4 formation potential (N m^3)
W : Disposed waste to landfill site (ton/yr)
k : Reaction constant
t : Modelling period (yr)
i : Kinds of waste
j : Disposed year

Where, among various methods like BMP test, Lysimeter [12], BMP test results carried by SLC (Sodokwon Landfill Site Management Corp.) were used for waste constitutional L [13]. For the CH_4 generation rate per waste constitutions, k, IPCC (Intergovernmental Panel on Climate Change) data was used. As IPCC suggests, the petroleum chemical substances like plastics were treated as non-decomposable for landfill and after landfill management period.

For modeling calibration, 2nd Landfill monitoring data during 2005-2009 was used; the modeling results were used for calculating and calibrating the amount of CH_4 from major emission routes [14]. The data from the year 2010 was omitted from the modeling calibration due to the irregular occurrences in that year, namely including gas suction maintenance. Also for calibration, the modeling was repeated by multiplying k by calibration factor f, and f= 1.74 was adopted as it displayed minimum deviation in −0.07%

Table 2. Data and variables used to estimate CH_4 emission amount from Sudokwon Landfill Site 2nd Landfill

Physical constitution	Food	Paper	Wood	Textiles	Others
W (10^3 ton)[a]	5,134	11,859	8,054	1,751	1,087
L (N m^3 CH_4/wet ton)	117.1	239.1	116.0	215.8	109.3
k (yr^{-1})[10]	0.15	0.06	0.03	0.06	0.08
k′ (yr^{-1})[b]	0.261	0.104	0.052	0.104	0.139

[a]Total estimated decomposing waste disposed to 2nd Landfill for 2000-2015
[b]k′=f·k, f=1.74

Table 3. Analyzing conditions of LFG sample for surface emission

Analyzer	Item	Condition
Methanizer (Donam Ins., Korea)	Column	10 cm×1/8 inch S.S., Nickel powder+Glass wool
	Gas flow	H_2: 30 mL/min
	Temperature	360 °C
GC/FID (GC-9A, SHIMADZU, Japan)	Column	2 m×3 mm S.S., Porapak Q (80/100 mesh)
	Detector	Flame Ionization Detector
	Carrier gas	N_2: 30 mL/min
	Injector/Detector temp.	130 °C
	Column temp.	60 °C (isothermal condition)

between monitoring data and modeling results [15]. Final input data and variables for first order decay model are shown in Table 2.

2. Estimation of CH_4 Emission

2-1. Compulsory Collection and Incinerator

CH_4 from landfill mainly consists of three sources such as the compulsory collection which can be used for energy source, the surface emission from slope, intermediate covering and final covering and the incineration by mobile incinerator.

In the case of compulsory collection, the actual measurement data was used for the time period of 2001-2009. For 2010-2015, modeling results were multiplied by the mean compulsory collection ratio during 2007-2009. This was because during this period the most profitable compulsory collection was performed for the optimal electric facility maintenance of a 50 MW electric power plant along with the act of prohibiting inflow of outer air to landfill inner space. For the ending year of disposing, 2016 and onward, the mean compulsory collection ratio 86.5% (2000-2005) of 1st Landfill under post control with the final covering is applied. This is due to the similarity of scale and structure of 1st Landfill with 2nd Landfill, and also because of the increasing compulsory collection ratio, resulting from the critical dropping of surface emission after the final covering.

Additionally, 36 mobile incinerators in gas exclusion wells and 72 in gas collection wells have been in service for CH_4 in 2nd Landfill for 4 years from 2004 to 2007. As for the mobile incinerators, incinerator flux data was applied to estimate the CH_4 amounts incinerated.

2-2. Surface Emission

Surface emission can be categorized into slope, intermediate covering and final covering. The annual mean values of the measured seasonal data during 2005-2009 by SLC were used to estimate the emission rates in each unit area. The actual measurement was conducted at 27 sites (15 for upper area, 12 for slope) in 1st Landfill, total 56 sites (42 for upper area, 14 for slope) in 2nd Landfill as shown in Table 3 [16].

For the CH_4 emission rate per area from slope and intermediate covering of 2nd Landfill, the actual measurement data from 2005-2009 was used [12]. For the time periods until 2004, the actual measurements were not made; the data of 2005 was applied. The mean value in 2007-2009 was applied for the time period of 2010-2015. Additionally, the mean value from 2005-2009 of 1st Landfill was applied emission rate per unit area from slope and final covering the period of 2016-2035.

The total annual emissions from slope, intermediate covering and final covering were calculated by multiplying the emission rates by the annual surface area according to landfill process. The slope and intermediate covering area for 2001-2010 was calculated according to landfill operating book, and the intermediate covering and final covering area for 2011-2015 was obtained by the expected disposing waste amounts and the related operation plan. The slope and final covering area for 2016-2035 were considered as fixed variables. Settlements and sinking incurring during the time period was neglected from this study due to the complexities in the estimation. The slope area's ratio against total surface area is relatively small. The annual area of slope, intermediate covering and final covering calculated with the above methods are as shown in Table 4.

The emission rates are affected by the total LFG emission flux. Therefore, the total emission is obtained from multiplying emission rate per unit area with the total area; then it is calibrated with total emission flux obtained from model. The calculating methods for compulsory collection, surface emission and incineration during the periods are illustrated in Table 5.

3. Evaluation Method for Climate Change Contributions

3-1. CO_2 Reduction Effects for Using CH_4 as an Energy Source

CH_4 estimated compulsory collection from Sudokwon Landfill

Table 4. Area of slope, intermediate covering and final covering by year (Unit: 10^3 m^2)

Year	2001	2002	2003	2004	2005	2006	2007	2008
Intermediate	960	1,520	1,441	1,762	2,142	2,204	2,126	2,035
Final	-	-	-	-	-	-	-	-
Slope	0	16	115	200	244	340	435	545
Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016-2035**
Intermediate	1,969	1,942	1,913	1,884	1,856	1,828	1,801	-
Final	-	-	-	-	-	-	-	1,773
Slope	625	660	697	735	775	818	863	911

Table 5. CH_4 flux calculation methods in each periods

Year	Intermediate covering & Slope	Compulsory	Incineration
2001-2003	$Q_{si}=A_i\cdot V_{2005}\cdot\left(\frac{M_i}{M_{2005}}\right)\cdot 24\cdot 365$	$Q_{ci}=Q_{mi}$	
2004			$Q_{Ii}=Q_{mi}$
2005-2007	$Q_{si}=A_i\cdot V_i\cdot 24\cdot 365$		
2008-2009			
2010-2015	$Q_{si}=A_i\cdot V_{aver}\cdot\left(\frac{M_i}{Q_{aver}}\right)\cdot 24\cdot 365$	$Q_{ci}=M_i\cdot R_{aver}$	
2016-2035	$Q_{si}=A_{fi}\cdot V_{aver1st}\cdot\left(\frac{M_i}{Q_{aver1st}}\right)\cdot 24\cdot 365$	$Q_{ci}=M_i\cdot R_{averc}$	

i : year
Q_{si} : CH_4 flux from slope, intermediate covering, final covering (m^3/yr)
Q_{ci} : CH_4 compulsory collection flux (m^3/yr)
Q_{Ii} : CH_4 incineration flux by mobile incinerator (m^3/yr)
Q_{aver} : mean CH_4 total flux for 2007-2009 (m^3/yr)
$Q_{aver1st}$: mean CH_4 total flux of 1st Landfill for 2005-2009 (m^3/yr)
Q_{mi} : actual measurement data of CH_4 compulsory collection and incineration (m^3/yr)
Q_{Ti} : CH_4 total flux of surface emission, compulsory collection and incineration (m^3/yr)
A_i : area of slope, intermediate covering (m^2)
A_{fi} : area of final covering (m^2)
V_{2005} : CH_4 emission rate of 2005 from slope, intermediate covering ($m^3/m^2\cdot hr$)
V_i : CH_4 emission rate from slope, intermediate covering ($m^3/m^2\cdot hr$)
V_{aver} : CH_4 emission mean rate from slope, intermediate covering for 200702009 ($m^3/m^2\cdot hr$)
$V_{aver1st}$: mean CH_4 emission rate of 1st Landfill's final covering for 2005-2009 ($m^3/m^2\cdot hr$)
M_i : CH_4 total flux by modeling (m^3/yr)
M_{2005} : CH_4 total flux of 2005 by modeling (m^3/yr)
R_{aver} : mean ratio of CH_4 in LFG for 2007-2009
R_{averc} : mean compulsory collection ratio of 1st Landfill for 2005-2009

Table 6. Carbon emission rate of each fossil fuels[16]

(Unit: tC/TJ)

Crude oil	Natural gas liquid	Gasoline	LPG	Natural gas (dry)	Anthracite
20	17.2	18.9	17.2	15.3	26.8

Site 2nd Landfill (2001-2035) was converted into CO_2 in the case of fossil fuels replacement using the method of IPCC, and was evaluated as reduction amount of global warming gas. First, as in Eq. (2), compulsory collection amount was converted into kcal/N m^3 and then into Joules by using factors F_b and F_c, and again into Carbon and CO_2 of each fossil fuels of Table 6 based on the weight basis by using F_d and molecular weight ratio 44/12 [17]. For CH_4 incineration efficiency, IPCC default value, 0.995 was applied.

$$Q_{C\text{-}CO_2}=Q_{C\text{-}CH_4}\cdot F_a\cdot F_b\cdot F_c\cdot F_d\cdot\frac{44}{12}\cdot 10^{-9} \quad (2)$$

$Q_{C\text{-}CO_2}$: CO_2 reduction amount by using compulsory collected CH_4 for energy source (Ton)
$Q_{C\text{-}CH_4}$: Total CH_4 amount by compulsory collection (N m^3)
F_a : Incineration efficiency (0.995)
F_b : CH_4 low-heating value (8,560 kcal/N m^3)
F_c : CH_4 energy converting rate (4.1868 kJ/kcal)
F_d : Carbon emission rate for each fossil fuels (Ton/TJ)

3-2. Evaluation Method on Contribution to Climate Change

Among LFG emitted from the surface, only CH_4 is taken as climate change affecting gas. CO_2 was omitted because CO_2 is reemitted from decomposed biomass like wood, paper and food by microorganisms. CO_2 generated from mobile incinerator or from incineration was excluded. As in Eq. (3), to quantitatively present the impact on climate change, amount of CH_4 emitted from surface was converted into CO_2 (Ton) by using GWP (global warming potential) index of 21 for CH_4 [18]. CH_4 of LFG is produced from biomass unlike fossil fuel, so GWP 20 was applied. And the temperature calibration from 20 ºC to 0 ºC and conversion volume to mass by multiply 44/22.4 was conducted.

$$Q_{C\text{-}CO_2}=Q_{C\text{-}CH_4}\cdot(21-1)\cdot\frac{273}{273+20}\cdot\frac{44}{22.4}\cdot 10^{-3} \quad (3)$$

$Q_{C\text{-}CO_2}$: Converted CO_2 amount of surface emitted CH_4 (Ton)
$Q_{C\text{-}CH_4}$: Total amount of surface emitted CH_4 (N m^3)

RESULTS AND DISCUSSION

1. CH_4 Generation Evaluation and Behavior Analysis at Major Emission Routes

Total CH_4 generation and estimated emission by first-order decay model and calibration methods are shown in Fig. 2. As the landfill operation continued, the compulsory collection and surface emis-

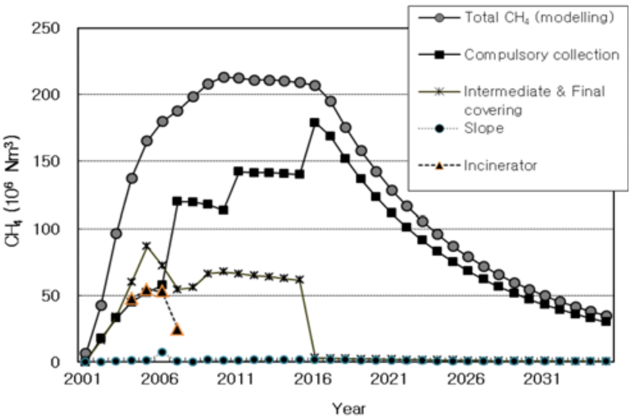

Fig. 2. Yearly CH_4 behavior trends (Sudokwon Landfill Site 2nd Landfill, 2001-2035).

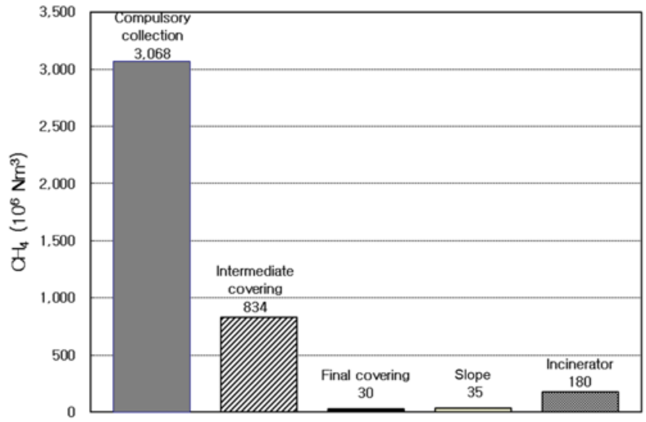

Fig. 3. CH_4 emission amount from each emission route (Sudokwon Landfill Site 2nd Landfill, 2001-2035).

sion flux was increasing as CH_4 flux increased. As the landfill operation progressed, effective compulsory collecting system was established. The compulsory collection flux shows an inverse proportional relationship with surface emission flux. From 2007 to 2009, the compulsory collection flux and surface emission flux displayed relatively constant rates due to 50 MW electric power plant operation.

From 2016, the year anticipated for the final covering due to decommissioning, compulsory collection amount was expected to increase drastically. On the other hand, the surface emission amount was also expected to show drastic reduction. After this time period, compulsory collection was expected to be diminished gradually in proportion to the diminution of LFG generations (Fig. 2).

As shown in Table 7 and Fig. 3, the total CH_4 amount which can be collected from Sudokwon Landfill Site 2nd Landfill during 2001-2035 is $3,067\times10^6$ N m^3, and the total CH_4 incineration amount by mobile incinerator during 2004-2007 was 180×10^6 N m^3. Additionally, from 2001 to 2035 the total CH_4 emission amount from landfill slope, intermediate covering and final covering is 899×10^6 N m^3. The surface emission amount from slope during the same period is 35×10^6 N m^3, and 834×10^6 N m^3 from intermediate covering during 2001-2015.

In Addition, after the decommissioning of the landfill, the total emission from final covering is 30×10^6 N m^3. In the total CH_4 amount of surface emission and compulsory collection of 2nd Landfill, the compulsory collected accounted for 74.0%. 95.0% (854×10^6 N m^3) of total surface emission emitted during the landfill period 2001-2015. After the final covering (2016-2035) only 5.0% (45×10^6 N m^3) was emitted because of the influences of LFG diminution and the final covering which has significantly smaller unit area emission rate, compared to intermediate covering. And as shown in Table 8, intermediate covering accounted for the most of the surface emission from landfill site during landfill operation with the amount of 92.8% (834×10^6 N m^3) in the total surface emission.

2. Climate Change Reduction Effects from Fossil Fuel Replacement

In this study, the total energy potential of compulsorily collected

Table 7. Total CH_4 behavior (Sudokwon Landfill Site 2nd Landfill, 2001-2035) (Unit: 10^6 N m^3_CH_4/y)

Total	Compulsory collection	Surface				Incineration
		Sub total	Intermediate covering	Final covering	Slope	
4,146	3,068	899	834	30	35	180
100.0 (%)	74.0	21.7 (100.0)	(20.1)	(0.7)	(0.8)	4.3

Table 8. Comparison of CH_4 emission amount (Sudokwon Landfill Site 2nd Landfill, 2001-2035) (Unit: N m^3_CH_4/y, (%))

	Total	Landfill period	After Landfill
Total	898,516,072 (100.0)	853,828,266 (95.0)	44,687,807 (5.0)
Slope	35,104,762 (3.9)	20,066,810	15,037,952
Intermediate covering	833,761,455 (92.8)	833,761,455	-
Final covering	29,649,854 (3.3)	-	29,649,854

Table 9. Carbon and CO_2 emission reduction effect by each fossil fuels (Unit: Ton)

	Crude oil	Natural gas liquid	Gasoline	LPG	Natural gas (dry)	Anthracite
Carbon	2,187,971	1,881,655	2,067,633	1,881,655	1,673,798	2,931,881
$Q_{C\_CO_2}$	8,022,560	6,899,402	7,581,319	6,899,402	6,137,259	10,750,231

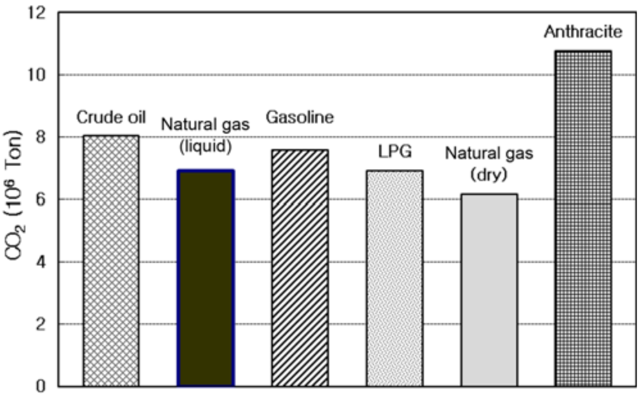

Fig. 4. CO_2 reduction quantities by fossil fuels.

LFG and fossil fuel replacement effect was analyzed. The results of comparison by Eq. (2) are depicted in Table 9, illustrating several kinds of fossil fuels which can be replaced by CH_4 for electricity generation, vehicle and other fuels usages. As shown in Table 9 and Fig. 4, the case replacing anthracite was the greatest as $10{,}750\times10^3$ CO_2 tons and natural gas (dry) was the smallest as $6{,}137\times10^3$ CO_2 tons and in crude oil bases $8{,}023\times10^3$ CO_2 tons. Production of electricity is the most common for using LFG as an energy source. Use of LFG with the natural gas is also generally feasible for vehicle fuel. But the efficiencies in energy production are different depending on fuel type on the basis of mass and energy balance. The energy production efficiency can affect climate change. For a specific evaluation for each fossil fuel, the characteristics of facilities and energy efficiencies need to be considered through additional research.

3. The Impact on Climate Change by Landfill

For the evaluation of CO_2 reduction effect for use of compulsorily collected CH_4 as an energy source and the impact on climate change. Surface emitted CH_4 (899×10^6 N m^3) was converted into CO_2 amount by Eq. (3). As a result of calculation, the climate change impact by CH_4 emitted from the slope, intermediate covering and final covering of Sudokwon Landfill Site 2nd Landfill during 2001-2035 was 32.9×10^6 Ton in CO_2 bases (Table 10).

As shown in Table 11, on CO_2 bases, the reduction amount of global warming gas by converting compulsorily collected CH_4 to energy source was about 19-33% of the contribution level by surface emitted CH_4. In other words, against the control effect of the compulsory suction system on CH_4 surface emission, it can be concluded that the waste landfill can have significantly adverse effects on climate change. And the importance of intermediate covering especially depends on its relative area and operating time. So in the case of a large-scale landfill like Sudokwon Landfill Site 2nd Landfill, more stringent guidelines are needed for intermediate covering for physical function and competences.

CONCLUSIONS

CH_4 compulsory collection and surface emission amount of Sudokwon Landfill Site 2nd Landfill was estimated by using actual measurement data and first-order decay model to analyze the impact on climate change by waste landfill method. In addition, on the basis of such estimated amount, surface emission amount and reduction amount by replacing fossil fuels to CO_2, are calculated. The following are the findings.

1. The total CH_4 amount during 2001-2035 from Sudokwon Landfill Site 2nd Landfill is $4{,}146\times10^6$ N m^3, and during the same period the total CH_4 emission amount from landfill slope, intermediate covering and final covering is 899×10^6 N m^3.
2. 95% (854×10^6 N m^3) of total surface emission amount is emitted during the landfill period (2001-2015), and after final covering (2016-2035) only 5.0% (45×10^6 N m^3) is to be emitted. Especially, the surface emission amount of landfill site is emitted from intermediate covering during landfill operation and the amount constitutes 92.8% (834×10^6 N m^3) of total surface emission.
3. If the collected CH_4 is entirely used in replacing fossil fuel, the CO_2 reduction effects are $10{,}750\times10^3$ CO_2 tons in anthracite, $8{,}023\times10^3$ CO_2 tons crude oil or $6{,}137\times10^3$ CO_2 tons natural gas (dry).
4. The climate change impact by CH_4 which is emitted from the slope, intermediate covering and final covering of Sudokwon Landfill Site 2nd Landfill during 2001-2035 is 32.9×10^6 tons in CO_2 bases. On CO_2 bases, the reduction amount of global warming gas by converting compulsorily collected CH_4 to energy source is about 19-33% of the contribution level by surface emitted CH_4.

It can be concluded that against the beneficial effects of the established LFG collecting system, the landfill remains as a system providing significantly adverse influences on climate changes. Especially, CH_4 surface emission under landfill process from intermediate covering proved to be the highest contributing factor. Accordingly, the

Table 10. Climate change contributions by surface emission route

	Total	Slope	Intermediate covering	Final covering
CH_4 (N m^3)	898,516,072	35,104,762	833,761,455	29,649,854
CO_2 (Ton)	32,889,368	1,284,978	30,519,084	1,085,306
Proportion (%)	100.0	3.9	92.8	3.3

Table 11. The reduction percentage compare to CH_4 from landfill (by fossil fuel)

Fuels	Crude oil	Natural gas liquid	Gasoline	LPG	Natural gas (dry)	Anthracite
$\frac{Q_{C\text{-}CO_2}}{Q^*_{S\text{-}CO_2}}$ (%)	24.4	21.0	23.1	21.0	18.7	32.7

*$Q_{S\_CO_2}$: total surface emitted CO_2

present landfill facility establishment standards and operating guidelines centered on sanitary landfill require further improvements with objectives to reduce climate change impacts.

REFERENCES

1. R. Stahlberg and Y. J. Lim, *Korea Assoc. Counc. Incineration Technol.*, 77 (2003).
2. R. Stahlberg and U. Feuerriegel, *Chem. Technol.*, **46**, 257 (1994).
3. Y. J. Kim, J. Y. Lee, J. M. Koo and Y. T. Kang, *Korean J. Air-cond. and Refrig. Eng.*, **22**, 181 (2010).
4. A. Tolis, A. Rentizelas, K. Aravossis and I. Tatsiopoulos, *Waste Manage. Res.*, **28**, 988 (2010).
5. 2009 National Waste Generation and Treatment Inventory, Ministry of Environment, Korea, 14 (2010).
6. Sudokwon Landfill Statistics Yearbook, Sudokwon Landfill Site Management Corp., **8**, 35 (2010).
7. Final Design for Sudokwon Landfill Site 3th Landfill Infrastructure Construction, Sudokwon Landfill Site Management Corp., 171 (2009).
8. Feasibility Study Report for Sudokwon Waste Energy Construction Project (2^{nd} : 3^{rd}), Sudokwon Landfill Site Management Corp., 147: 62 (2009).
9. S. K. Chun, *Korea Soc. Waste Manag.*, **27**, 727 (2010).
10. J. B. Won, S. Kim and J. Y. Jung, *Korea Soc. Waste Manag.*, **26**, 577 (2009).
11. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change (IPCC), 3.17 (2007).
12. M. El-Fadel and M. Massoud, *Environ. Technol*., **21**, 965 (2000).
13. A Study on The Monitoring & Prediction System Building Measures for LFG and Leachate of Sudokwon Landfill Site, Sudokwon Landfill Site Management Corp., 210 (2004).
14. 2009 LFG Site Monitoring and Emission Characteristics Analysis for Sudokwon Landfill Site, Sudokwon Landfill Site Management Corp., 64 (2010).
15. S. K. Chun, *Korean Soc. Environ. Eng.*, **32**, 943 (2010).
16. Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber User's Guide, US EPA (United States Environmental Protection Agency), 3-11 (1986).
17. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change (IPCC), 1.5-1.6 (1996).
18. L. D. Danny Harvey, *Energy Policy*, **21**, 24 (1993).