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Article

Environmental Effects of Sewage Sludge Carbonization and Other Treatment Alternatives

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Abstract: Carbonization is a newly developed process that converts sewage sludge to biocoal, a type of solid biomass that can partially substitute for coal during power generation. This study presents an assessment of the environmental effects of various sewage sludge treatment processes, including carbonization, direct landfills, co-incineration with municipal solid waste, and mono-incineration in Taiwan. This assessment was conducted using the life cycle assessment software SimaPro 7.2 and the IMPACT2002+ model. Results show that carbonization is the best approach for sewage sludge treatment, followed in descending order by co-incineration with municipal solid waste, direct landfills, and mono-incineration. The carbonization process has noticeable positive effects in the environmental impact categories of terrestrial ecotoxicity, aquatic ecotoxicity, land occupation, ionizing radiation, aquatic eutrophication, non-renewable energy, and mineral extraction. For the emission quantity of greenhouse gases, landfilling has the greatest impact (296.9 kg CO_2 eq./t sludge), followed by mono-incineration (232.2 kg CO_2 eq./t sludge) and carbonization (146.1 kg CO_2 eq./t sludge). Co-incineration with municipal solid waste has the benefit of reducing green house gas emission (–15.4 kg CO_2 eq./t sludge). In the aspect of energy recovery, sewerage sludge that has been pretreated by thickening, digestion, and dewatering still retains a high moisture content, and thus requires a significant amount of energy use when used as a substitute solid fuel. Therefore, the carbonization of sewage sludge would be a more sustainable option if the energy delivery and integration processes are made more efficient.

Keywords: sewage sludge; carbonization; life cycle assessment; biocoal; environmental impact

1. Introduction

Because of high population growth and urban planning in Taiwan, the prevalence of public sewage systems reached 30% of the population in 2012, and is expected to increase to 36% by 2014 [1]. Thus, sewage sludge production will increase with the expansion of the sewage treatment system, and should reach up to 1040 t/day by 2014 [2]. Sewage sludge generally contains pollutants such as human pathogenic organisms, and must be disposed of in ways that reduce environmental and public health effects.

Most sewage sludge in Taiwan is currently disposed of in landfills, with the remainder being co-incinerated with municipal solid waste (MSW). Existing crane and grapple-feeding devices have difficulty handling the pasty sludge cake with MSW, and the sludge degrades combustion efficiency. Thus, the co-incineration ratio is limited. Some MSW incineration plants even ban sewage sludge. The scarcity of available landfills and limited capacity of co-incineration are pressing problems. Other solutions for handling sewage sludge in more environmentally friendly ways, and recovering its energy, have caused great concern in recent years.

The imported energy ratio in Taiwan is as high as 99.4%, and energy security is unfavorable [3]. Finding alternative energy sources, such as bioenergy, is necessary. Carbonization technology can transform sludge into a carbon-containing product that can be used as biocoal and co-fired with fossil coal to generate electricity in power plants [4–8]. Carbonizing sludge reduces its volume to approximately one-eighth of the sludge cake, increases its calorific value, removes its odor, and improves its combustibility and grindability, making it a better co-firing material for pulverized coal power plants [4,5,9]. Reference plants applying sewage sludge carbonization technology in Japan and North America have successfully demonstrated its feasibility [8–11]. These applications advance the goals of using sewage sludge as an energy resource and simultaneously reducing greenhouse gas emissions and coal extraction.

Life cycle assessment (LCA) is a method of evaluating the environmental effects associated with a product, process, or service throughout its life cycle. The LCA method is generally performed according to ISO14040 standards, which define the principles and framework of LCA [12]. Researchers have also applied LCA to sewage sludge management. Hospido *et al.* [13] compared three alternative sewage sludge post-treatments (agricultural use, incineration, and pyrolysis) and then assessed the energy reuse strategy used in pyrolysis. Hong *et al.* [14] combined LCA and LCC (*i.e.*, life cycle cost) to estimate the environmental and economic effects of six alternative sewage sludge treatments. Their results indicate that dewatered sludge combined with electric melting is an environmentally optimal and economically affordable method. Murray *et al.* [15] also applied life cycle environmental and life cycle cost assessments to nine alternative sewage sludge treatments. Their results indicate that coal-fired incineration is the most environmentally and economically costly of all treatments. However, no study has presented the LCA of sewage sludge carbonization. Because carbonization is increasingly being adopted in several countries and is a candidate for sludge treatment in Taiwan, understanding the potential effects of this biomass usage method is necessary.

The objectives of this study are to simulate the sewage sludge carbonization process, using local sludge properties, to evaluate the environmental effects and benefits of the carbonization process using LCA. This study also uses LCA to investigate current approaches for sewage sludge treatment, including direct landfills, co-incineration with MSW, and mono-incineration for comparison.

2. Simulation of the Sewage Sludge Carbonization Process

Because no inventory is available within the existing LCA database applicable to carbonization, this study adopts an energy model developed by Maski *et al.* for biomass pretreatment [16] and previous research results of biomass torrefaction [17–19]. This study also refers to a batch-type carbonation experiment, conducted by Park and Jang [4], specific to dried sewage sludge at 300–500 °C for 30 min. Koga *et al.* [8] also reported a sewage sludge carbonization system handling 40–60 kg/h of dewatered sludge at a 500 °C carbonation temperature to produce biocoal. Therefore, the simulated carbonization process in this study assumed dewatered sludge to be bone dried at 100 °C, and subsequently carbonized at 450 °C for 30 min in the absence of oxygen. Carbonized liquid and volatile gases were collected and recovered for their heat energy [20,21], which was supplied to the drying and carbonization units through a combustor and heat exchanger. The final carbonized product or biocoal, which had properties similar to fossil coal, can generate carbon neutral bioenergy at a pulverized coal power plant.

The following equations were used to simulate the sewage sludge carbonization process:

(1) The energy use of a drying unit ($E_{R,D}$, MJ/kg) is represented by:

$$E_{R,D} = \left\{ \left(\frac{M_{wet}}{100} \right) \times \left[C_{p,w} \times (373 - T_i) + L_{v,w} \right] + \left(\frac{DB_{wet}}{100} \right) \times C_{p,b} \times (373 - T_i) \right\} \times e_{f,d}^{-1} \quad (1)$$

where M_{wet} (wt %) is the moisture content of sewage sludge; DB_{wet} (wt %) is the percentage of dry solid in sewage sludge (note: $M_{wet} + DB_{wet} = 100$ wt %); $C_{p,w}$ (MJ/kg K) is the specific heat of water = 0.004187 MJ/kg K; T_i (K) is the initial temperature of sewage sludge = 298 K; $L_{v,w}$ (MJ/kg) is the latent heat of water at its boiling point = 2.27 MJ/kg; $C_{p,b}$ (MJ/kg K) is the specific heat of sewage sludge = 0.001763 MJ/kg K [18]; and $e_{f,D}$ is the efficiency of the drying unit (assumed to be 0.85 in this study, a relatively high efficiency).

(2) The energy use of a carbonization unit ($E_{R,C}$, MJ/kg) is represented by:

$$E_{R,C} = \frac{C_{p,b} \times (T_C - 373)}{e_{f,c}} \quad (2)$$

where T_C (K) is the carbonization temperature, and $e_{f,C}$ is the efficiency of the carbonization unit, set to 0.85 in this study.

(3) In a combustor and heat exchanger, available energy is derived from the combustion of volatile gas and carbonized liquid, where available energy from volatile gas ($E_{A,CG}$, MJ/kg) and available energy from carbonized liquid ($E_{A,CL}$, MJ/kg) are represented by:

$$E_{A,CG} = \frac{1}{3} LHV_{volatile} \times DB \times y_{MG} \times e_{f,c} \times (1 - H_L) \quad (3)$$

and:

$$E_{A,CL} = \frac{1}{3} LHV_{liquid} \times DB \times y_{ML} \times e_{f,c} \times (1 - H_L) \quad (4)$$

The terms $LHV_{volatile}$ (MJ/kg) and LHV_{liquid} (MJ/kg) represent the heating value of the volatile gas and carbonized liquid generated by the carbonization unit, respectively, and *DB* (kg) is the weight of dried sludge, y_{MG} is the volatile gas yield, y_{ML} is the carbonized liquid yield [calculated by Equation (5)], $e_{f,C}$ is the efficiency of the combustor unit (assumed to be 0.85), and H_L is the heat loss of the heat exchanger (assumed to be 0.5%).

(4) The product yield (y_M) is defined according to mass by [22]:

$$y_M = \left(\frac{m_{out}}{m_{in}} \right)_{daf} \quad (5)$$

where m_{in} is the mass of the biomass input, and m_{out} is the mass of product output of a carbonization unit (note: *daf* = dry and ash free).

Figure 1 shows the simulation results of sewage sludge carbonization based on the properties of dewatered sewage sludge after anaerobic digestion from a local sewage treatment plant and experimental results of carbonization yield [23,24] (Table 1). Mass and energy balance calculations show a 0.08 (*daf*) product yield (y_M), 3.19 MJ/kg total energy required of units, 0.14 MJ/kg available energy from volatile gas ($E_{A,CG}$), and 0.5 MJ/kg available energy from carbonized liquid ($E_{A,CL}$). The supplementary information (Table A1) explains the nomenclature and provides parameter values. Although the simulation process is a simplified form, this approach presents a feasible method to access the LCA of sewage sludge carbonization. By changing the efficiencies of the drying unit and carbonization unit from 0.85 to 0.65 (decreasing 20%), the overall required energy increases 25% and the available energy from volatile gas and carbonized liquid decreases 19%. The influence of the assumed efficiency of each unit on the LCA results can be estimated accordingly.

Figure 1. Mass and energy balances of the sewage sludge carbonization process.

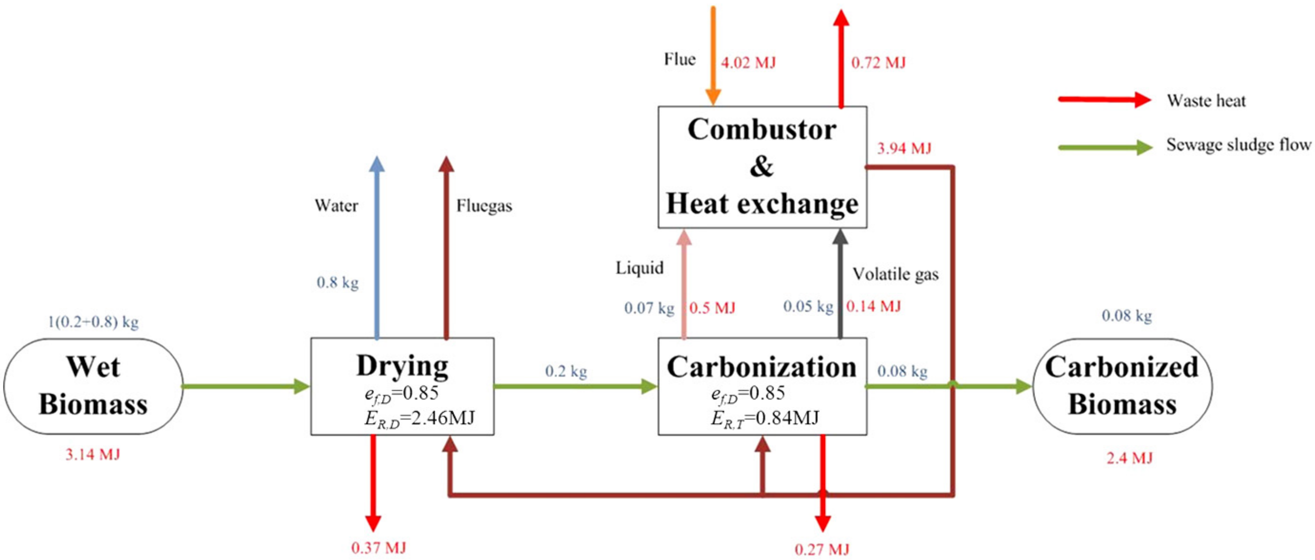


Table 1. Sewage sludge characteristics.

Dewatered sludge characteristics*	**Value**
Moisture (wt %)	80
High heating value $_{dry}$ (MJ/kg)	15.18
Proximate analysis (dry basis, wt %)	
Ash content	35.2
Volatile matter	64.8
Elemental analysis (dry and ash free basis, wt %)	
C	54.60
H	7.69
N	4.52
O	30.29
S	2.52
Experimental results of carbonization yield (dry and ash free basis, wt %)**	
Solid yield	39.14
Liquid yield	34.09
Volatile gas	26.77

Notes: * Source: [2]; ** Source: [23,24], recalculated by this study at 450 °C.

3. Materials and Methods of LCA

The LCA software SimaPro 7.2 (PRé Consultants, Amersfoort, The Netherlands) was used to assess the environmental effects of four sewage sludge treatment scenarios: carbonization, mono-incineration, landfill, and co-incineration with MSW. The IMPACT2002+ model (included in SimaPro 7.2) was used to characterize environmental effects [25] by combining midpoint assessments with various damage categories.

3.1. Functional Unit

The functional unit is defined as the unit for comparison in a life cycle inventory. Specifically, this study adopts the management of 1 t of dewatered sludge (moisture content 80%) as the functional unit on which all material and energy use, energy recovery, and emissions are based.

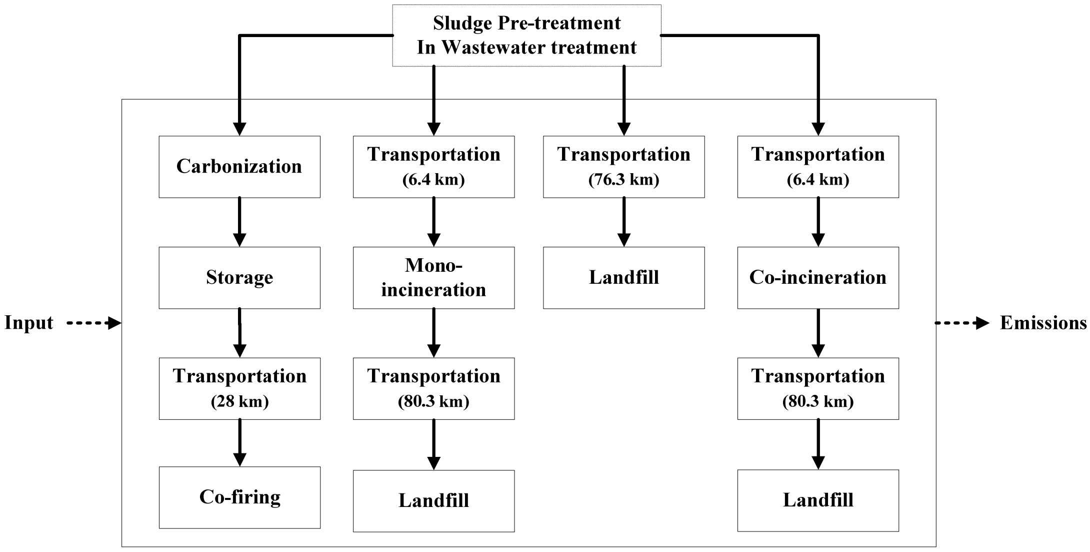
3.2. System Boundaries

Dewatered sludge after anaerobic digestion from the Dihua sewage treatment plant in Taipei City (Taiwan) was adopted as an example for evaluation in this study, and its characteristics are detailed in reference [26]. Figure 2 shows the system boundaries of the study: carbonization and mono-incineration were hypothesized alternatives, whereas landfill and co-incineration with MSW were modeled according to current practice. The considerations for each system included the following factors:

(a) Carbonization of dewatered sludge and co-firing of biocoal (1% by heat input) at the Linkou coal power plant, New Taipei City, Taiwan, considering coal substitution, electricity generation, and heat recovery.

(b) Mono-incineration of dewatered sludge at certain industrial waste incineration plants without production of electrical energy, considering heat recovery.
(c) Sanitary landfill of dewatered sludge at Wujie Township, Yilan County, Taiwan, without considering methane recovery.
(d) Co-incineration of dewatered sludge (3% by weight) with MSW at the Beitou MSW incineration plant, New Taipei City, Taiwan, in which waste to electricity was considered.

Figure 2. System boundary. Values in parentheses are transportation distances.



3.3. Inventory Data Source

3.3.1. Energy Use and Recovery

This study investigates the inventories of energy use and recovery to assess the potential net energy benefits of different sludge treatments. For all scenarios, electricity was the primary energy consumed, and its impacts on environment were characterized by the actual electricity structure in Taiwan (coal-fired: 50%; LNG-fired: 25%; nuclear: 17%; oil-fired: 4%; hydro: 3%; waste: 1%). For the assessment of energy recovery in the carbonization scenario, the quantity of recycled heat (640 MJ), coal substitution (80 kg), and electricity generation (105 kWh) resulting from co-firing was derived from simulation results and heating values conversion of biocoal (Figure 1). The inventory also includes the effects of sludge transportation by trucks (>28 t) and coal substitution on coal mining and ocean shipping.

Table A2 lists energy and material inputs for mono-incineration scenario. The mono-incineration scenario recovered heat energy (349.4 MJ) during the incineration process [13]. The co-incineration scenario generated electricity (0.21 kWh) by the co-incineration of sludge with MSW [27]. The landfill scenario recovered no energy (methane).

3.3.2. Data Quality

Other inventory data used in this study were obtained from three main sources:

(1) SimaPro 7.2 databases: The LCA, Ecoinvent, Industry data 2.0, IDEMAT 2001, and LCAfood databases contained in SimaPro software were used for the inventory of the four scenarios

(carbonization, direct landfills, co-incineration with municipal solid waste, and mono-incineration). This study also investigates the variables of input, output, emission, and waste disposal stages.

(2) Operational data: Data used for the co-incineration scenario, such as electricity generation and electricity consumption, were obtained from practical data logging at the Beitou MSW incinerator Taiwan.

(3) Literature and theoretical calculation: Neither carbonization nor mono-incineration of sewage sludge are practiced in Taiwan. Therefore, the inventory of the mono-incineration scenario was derived from previous studies, and theoretical calculations were applied to the carbonization scenario based on Equations (1)–(5).

4. Impact Assessment and Discussion

4.1. Carbonization Scenario

The sewage sludge carbonization process was divided into several steps to identify the major sources of environmental effects and their consequences (Table 2). Results indicate that the drying unit created the highest environmental effect of all categories. Non-renewable energy and global warming were the categories most affected by drying and carbonization because of their high energy use. Recycling heat during carbonization had a positive effect on all categories. In addition, biocoal storage increased particulate emissions and land use.

Table 2. Characterization of the carbonization scenario.

Carbonization and co-firing			Carbonization process					Co-firing of biocoal and coal in power plant		
Impact category	**Unit**	**Total**	**Drying**	**Carbonization**	**Energy Reuse**	**Carbonization Facility**	**Biocoal Storage**	**Co-firing**	**Alternative coal**	**Electricity production**
Carcinogens	kg C_2H_3Cl eq.	1.98	1.66	0.51	−0.32	0	0	0.32	−0.08	−0.11
Non-carcinogens	kg C_2H_3Cl eq.	2.82	0.23	0.04	−0.02	0	0	2.96	−0.17	−0.22
Respiratory inorganics	kg $PM_{2.5}$ eq.	0.08	0.05	0.01	0.00	0	0.04	0.08	−0.04	−0.06
Ionizing radiation	Bq C^{-14} eq.	−1182	1556.3	158.23	−39.90	0.21	0	22.68	−274.61	−2,605.29
Ozone layer depletion	kg CFC^{-11} eq.	0.00003	0.00	0.00	0.00	0	0	0.000001	−0.000001	−0.000002
Respiratory organics	kg C_2H_4 eq.	0.03	0.05	0.01	−0.01	0	0	0.004	−0.02	−0.01
Aquatic ecotoxicity	kg TEG water	−22,412	3,952.9	671.52	−326.1	0.94	0	1,546	−23,768.1	−4,489.73
Terrestrial ecotoxicity	kg TEG soil	−6,003	933.3	161.68	−79.61	0.31	0	60.87	−6,044.6	−1,035.48
Terrestrial acid/nutria	kg SO_2 eq.	1.12	1.26	0.24	−0.12	0	0	2.47	−1.45	−1.29
Land occupation	m^2 land arable · year	−0.85	0.15	0.02	−0.01	0	0.06	0.02	−0.88	−0.22
Aquatic acidification	kg SO_2 eq.	0.36	0.34	0.06	−0.03	0	0	0.65	−0.27	−0.39
Aquatic eutrophication	kg PO_4 eq.	−0.0004	0.00	0.00	0.00	0	0.0000002	0.0001	−0.0006	−0.001
Global warming	kg CO_2 eq.	146.62	209.02	55.79	−34.15	0.01	0	9.37	−16.00	−77.42
Non-renewable energy	MJ primary	−1122.9	3,896.4	1,062.72	−655.6	0.15	0	15.33	−4,178.8	−1,263.00
Mineral extraction	MJ surplus	−0.02	0.18	0.04	−0.02	0	0	0.02	−0.13	−0.12

This study assumes that the biocoal produced from the carbonization process will be used for co-firing with coal in power plants. As Table 2 shows, the overall results of the carbonization scenario generated positive effects in the categories of terrestrial ecotoxicity, aquatic ecotoxicity, land occupation, ionizing radiation, aquatic eutrophication, non-renewable energy, and mineral extraction. These benefits resulted primarily from coal substitution and bioelectricity generation.

4.2. Comparison of Scenarios

In addition to the benefits and advantages of the carbonization scenario, this study presents a comparison of the results of four sewage sludge treatment scenarios. Figure 3 shows the characterization of the midpoint environmental effects for these scenarios. The carbonization scenario had the highest effect on ozone layer depletion and respiratory organics. Mono-incineration had the greatest effect on mineral extraction, non-renewable energy, aquatic acidification, terrestrial acid/nutrients, terrestrial ecotoxicity, ionizing radiation, and respiratory inorganics. The landfill scenario had the greatest effect on global warming, aquatic eutrophication, and land occupation. Co-incineration had the greatest effect on carcinogens and non-carcinogens and aquatic ecotoxicity.

Figure 3. Characterization of the mid-point environmental effects of four sludge-handling scenarios.

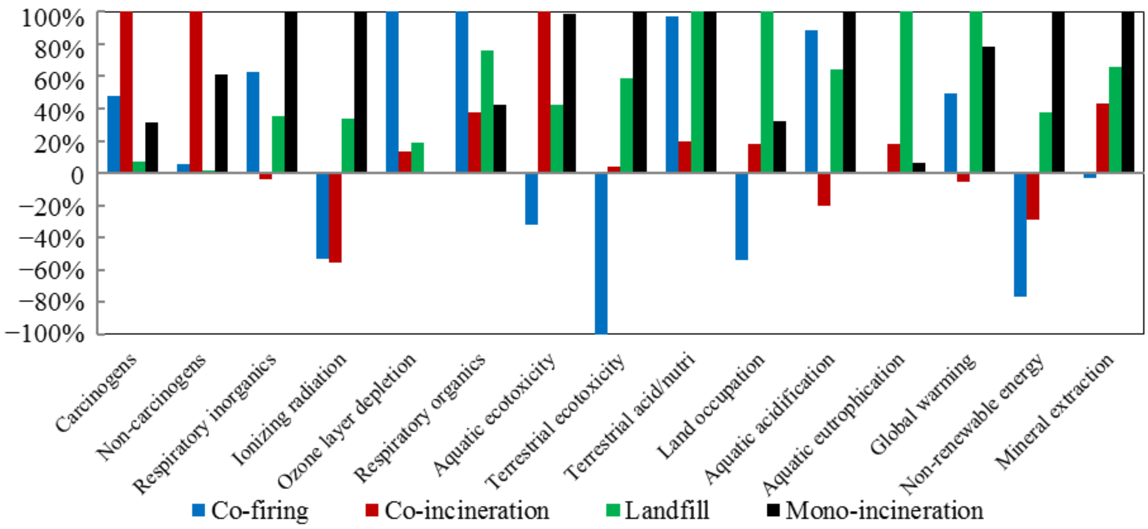


Table 3 shows the normalized results of the four scenarios for various damage categories: human health, ecosystem quality, climate change, and resources. Regarding damage to human health, mono-incineration and co-incineration damaged human health than the other scenarios. The effects of mono-incineration were caused primarily by the emission of particulates and nitrogen oxides, combined with the effluence of antimony and arsenic ions. The carbonization scenario had a beneficial effect on ecosystem quality because of the substitution of biocoal for some coal in the co-firing process. The landfill scenario had the greatest effect on climate change because of the greenhouse gas emitted during the landfill process. Mono-incineration had the greatest negative effect on resources because of its high energy use. Carbonization and co-incineration had positive effects on resources because of coal substitution and bioelectricity generation.

The single score column in Table 3 shows that the overall degree of environmental effect was mono-incineration > landfill > co-incineration > carbonization. Thus, carbonization combined with co-firing was the best scenario because it had the lowest environmental effect, followed by co-incineration, landfill, and mono-incineration in descending order. Table 3 shows the potential effect of the scenarios on global warming. Ranked in descending order of their greenhouse gas emissions, the scenarios were landfill (296.9 kg CO_2 eq.) > mono-incineration (232.2 kg CO_2 eq.) > carbonization (146.1 kg CO_2 eq.) > co-incineration (−15.4 kg CO_2 eq.). Landfills had the highest value because of the methane and carbon dioxide released during sludge decomposition. The greenhouse gas emissions of mono-incineration and carbonization primarily resulted from energy use. Only co-incineration showed a reduction in greenhouse gas emissions because of the bioelectricity generated during the incineration process.

Table 3. Results of normalization, single score, and GHG emission in four sludge–handling scenarios.

Item	**Normalized results of damage categories**				**Single score**	**GHG emission**
	Human health	**Ecosystem quality**	**Climate change**	**Resources**		
Unit	-	-	-	-	Pt	kg CO_2 eq.
Carbonization	0.0095	-0.0035	0.0148	−0.0074	0.013428	146.6
Co-incineration	0.0204	0.0003	−0.0016	−0.0028	0.016414	−15.4
Landfill	0.0048	0.0008	0.0300	0.0036	0.039208	296.9
Mono-incineration	0.0246	0.0012	0.0236	0.0097	0.059045	233.2

The evaluation of greenhouse gas emissions in this study is similar to that of other studies, with the exception of the novel presented carbonization scenario. Houillon and Jolliet [28] assessed a sludge treatment method consisting of landfill, incineration, and pyrolysis. Their results show that the landfill treatment returned the highest greenhouse gas emissions. Lundin *et al.* [29] and Svanstrom *et al.* [30] compared greenhouse gas emissions of sludge treatments, indicating that co-incineration was beneficial in reducing greenhouse gas emissions. However, the greenhouse gas emission calculations for the carbonization scenario were higher than that for co-incineration because of the energy used (in particular by the drying unit) during the carbonization process. According to the current study results, carbonization combined with co-firing is less advantageous than co-incineration with MSW alone because of two possible reasons. In the current study, the water content of the dried sludge was assumed to be 0%, whereas Koga *et al.* [8] reported that dewatered sludge was only partially dried (*i.e.*, until reaching 25% moisture content) before the carbonization step. In addition, this study assumes that the carbonization temperature is 450 °C (compared with 500 °C by Koga *et al.* [8]). This lower temperature may be more efficient and reduce energy use [4]. However, Lundin *et al.* [29] showed that the cost of co-incineration with waste was higher than using it in agricultural applications and incineration or fractionation combined with phosphorus recovery. Therefore, the co-incineration scenario may incur higher costs than other scenarios. Thus, environmental and economic effects should be cautiously considered when evaluating potential sludge treatments in the future.

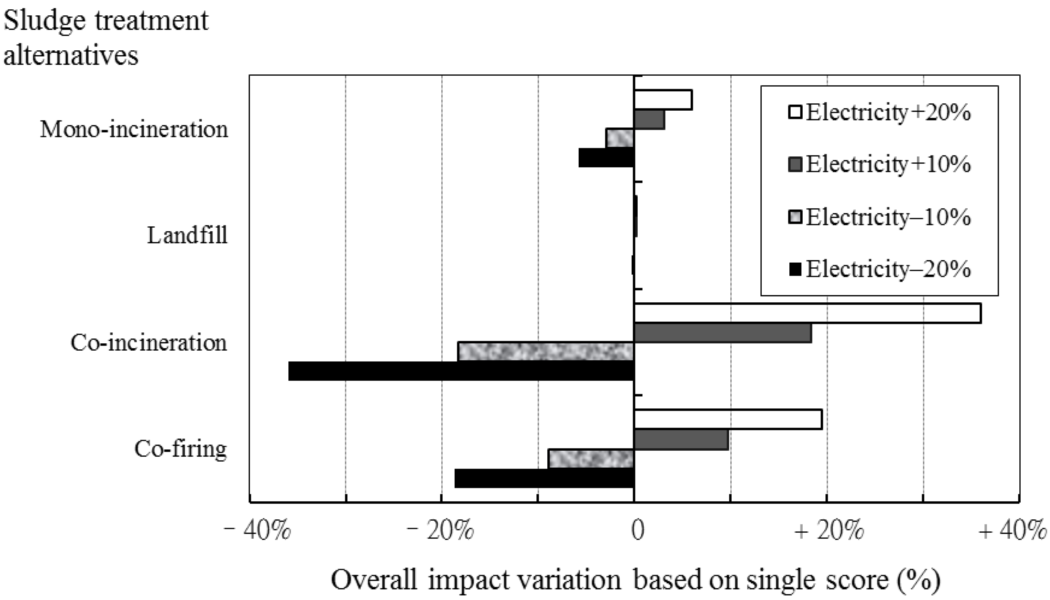
4.3. Sensitivity Analysis

Energy use is crucial in sewage sludge treatment options. Because all four scenarios in this study consume electricity, sensitivity analysis was performed using electricity consumption variances of ±10% and ±20%. The variations of single scores of the four sludge treatment scenarios were analyzed accordingly (Table 4). Results indicate that the co-incineration scenario was most sensitive to variation in electricity consumption. When the electricity consumption increased by 20%, the overall effect increased by 36% (Figure 4). Variation of electricity consumption had little effect on the environmental impacts of the landfill scenario.

Table 4. Results of single scores for electricity consumption variances.

Variation	Co-firing	Co-incineration	Landfill	Mono-incineration
Electricity −20%	1.09×10^{-2}	1.05×10^{-2}	3.91×10^{-2}	5.56×10^{-2}
Electricity −10%	1.22×10^{-2}	1.34×10^{-2}	3.92×10^{-2}	5.73×10^{-2}
Original case	1.34×10^{-2}	1.64×10^{-2}	3.92×10^{-2}	5.90×10^{-2}
Electricity +10%	1.47×10^{-2}	1.94×10^{-2}	3.93×10^{-2}	6.08×10^{-2}
Electricity +20%	1.60×10^{-2}	2.23×10^{-2}	3.93×10^{-2}	6.25×10^{-2}

Figure 4. Sensitivity analysis of electricity consumption for four sludge-handling scenarios.



5. Conclusions

This study presents an assessment of the environmental effects of four sewage sludge treatment options: carbonization, mono-incineration, direct landfills, and co-incineration with municipal solid waste. This study uses an energy model to simulate the process of sewage sludge carbonization and produces theoretical energy and mass balance data for conducting the LCA. The results of the four treatment scenarios show that carbonization was the most preferable sludge-handling option overall, followed by co-incineration, landfills, and mono-incineration in descending order.

However, the co-incineration option emitted less greenhouse gases than carbonization because the overall energy recovery ratio of electricity was higher during the incineration process than during carbonization. Although this analysis considers heat recovery during carbonization, electricity generation, and coal substitution during co-firing, the energy used in drying the dewatered sludge emitted more greenhouse gases, contributing greatly to the damage category of climate change. However, changing both the feeding water content after the drying process and the carbonization temperature may mitigate the energy use of the carbonization scenario.

The aspect of cost must also be considered in the assessment and selection of sewage sludge treatment options. Because the application of sewage sludge carbonization is currently receiving great attention from municipal authorities, the significance of sewage sludge as a valuable energy source may increase even more.

Acknowledgments

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Appendix

Table A1. Nomenclature and parameter values.

Nomenclature		Value
$C_{p,b}$	specific heat of sewage sludge (MJ/kg K)	0.001763
$C_{p,w}$	specific heat of water (MJ/kg K)	0.004187
DB	weight of dried sludge (kg)	0.2
DB_{wet}	percentage of dry solid in sewage sludge (wt %)	20
$E_{A,CG}$	available energy from volatile gas (MJ/kg)	-
$E_{A,CL}$	available energy from carbonized liquid (MJ/kg)	-
$E_{R,C}$	energy use of carbonization unit (MJ/kg)	-
$E_{R,D}$	energy use of drying unit (MJ/kg)	-
$e_{f,C}$	efficiency of the carbonization unit	0.85
$e_{f,C}$	efficiency of the combustor unit	0.85
$e_{f,D}$	efficiency of the drying unit	0.85
$L_{v,w}$	latent heat of water at its boiling point(MJ/kg)	2.27
LHV_{liquid}	heating value of the carbonized liquid(MJ/kg)	21.7*
$LHV_{volatile}$	heating value of the volatile gas(MJ/kg)	7.7*
M_{wet}	moisture content of sewage sludge(wt %)	80
m_{in}	mass of the biomass input (kg)	1
m_{out}	mass of product output (kg)	0.08
H_L	heat loss of the heat exchanger	0.005
T_i	initial temperature of sewage sludge (K)	298
T_C	carbonization temperature(K)	450
y_M	product yield (%)	-
y_{MG}	volatile gas yield (%)	26.77**
y_{ML}	carbonized liquid yield (%)	34.09**

Notes: *: Reference [24] and recalculated by this study. **: Reference [23] and recalculated by this study.

Table A2. Energy and material inputs for mono-incineration scenario.

Item	Active coal	Electricity	Heavy fuel oil	Lime	Natural gas	Polymer	NaOH	NH_3
Unit	kg/tDM	kWh/tDM	kg/tDM	kg/tDM	m^3/tDM	kg/tDM	kg/tDM	kg/tDM
Amount	0.4	80.08	2.78	6	13	1.42	2.44	0.744

Note: * tDM: 1 t of sludge in dry matter.

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