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Evaluation of food waste disposal options in terms of global warming and energy recovery: Korea

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Abstract

This study is aimed to evaluate and compare environmental impacts of various food waste management systems: anaerobic digestion, co-digestion with sewage sludge, and volume reduction using a garbage dryer followed by incineration from generation to final disposal. An environmental credit using life cycle assessment was employed to compare by-products. The entire disposal process, namely discharge, collection, transportation, treatment, and final disposal, was included in the system boundary. The functional unit was 1 tonne of food waste from households for each treatment option. Global warming potential of the category indicator was selected to assess the environmental impact of food waste disposal options. The net global warming potential (environmental credit) of the options (wet based) was 33 kg of carbon dioxide equivalent (CO_2-eq) for anaerobic digestion and −315 kg of CO_2-eq for incineration by renewable energy production as electricity, thermal energy, and primary materials avoided. We found that dryer-incineration option was an available alternative for food waste recycling in a metropolitan area in Korea.

Keywords: Food waste, Life cycle assessment, Global warming potential, Renewable energy, Environmental impact

Background

Energy recovery from wastes has a great potential for reducing CO_2 emissions and thereby resulting in greenhouse gas (GHG) emissions. Food wastes can be utilized as a substitution for traditional nature resource and energy under the situation of energy exhaustion and sustainable crisis nowadays. Due to the large amount and proportion in the municipal solid waste (MSW), food waste is expected to play an important role in the low-carbon economy and recycling-based society [1,2].

Anaerobic digestion for food wastes has been commonly used to produce energy from organic wastes [3-5]. It was reported that 1 m^3 of biogas had 21 MJ of energy by anaerobic digestion, and it could generate 2.04 kW h of electricity considering the 35% of generation efficiency [6]. Co-digestion of food wastes has been useful for energy recovery by increasing methane production from the sludge digestion in a sewage treatment plant (STP) [7]. It was known that the anaerobic co-digestion of sewage sludge and highly rich organics such as food wastes or

animal manure could increase biogas production [8,9]. Another research evaluated five food waste disposal options by life cycle assessment (LCA) and found that global warming potential (GWP) of the options were 273 kg of carbon dioxide equivalent (CO_2-eq) for anaerobic home composting, 82 kg of CO_2-eq for co-disposal with MSW, 52 kg of CO_2-eq for centralized composting, 13 kg of CO_2-eq for food waste processor system, and 0.3 kg of CO_2-eq for aerobic home composting [10]. GWP of each scenario was produced from 182 kg of food waste (wet based).

LCA is an effective environmental tool dealing with the complex interaction between the environment and a product or activity. Though LCA aims to be science-based, it involves a number of technical assumptions and value choices. In spite of its limitations, the environmental impacts obtained from LCA analysis are described as potential impacts because they are not specified in time and space. LCA has been conducted as a useful tool for a full cycle of MSW management, including collection, transport, waste treatment, infrastructure for waste treatment facilities, and production of energy and ancillary materials consumed [11].

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The geographical boundary of the study was Jungnang-gu, which is formed by the three mountains and located in Northeastern Seoul Metropolitan City; it is a separated area with large populations that are divided into five districts. The area of 18.53 km^2 occupies 3% of Seoul. Data were collected from the government of the district and plants in the study area.

The objectives of this study were to evaluate and compare the environmental impacts of food waste management systems including anaerobic digestion, co-digestion with sewage sludge, and incineration of dried food waste from the time of generation to final disposal. LCA methodology was used to analyze environmental impacts of the systems from the perspective of global warming. Tax issues in carbon emission regulations associated with climate change are to be an important matter of international concern. All countries of the world make an effort to mitigate climate change as activities that reduce GHG emissions. One of the options is to produce renewable energy from wastes that would result in GHG reduction [12]. Therefore, GWP of the result of characterization was finally selected as an environmental indicator to evaluate the impacts of global warming. Each GHG value is quantified as equalization of carbon dioxide by Intergovernmental Panel on Climate Change (IPCC) indicators [13]. The GHGs contain carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbon (CFCs), hydrofluorocarbon (HFCs), perfluorocarbon (PFCs), and sulfur hexafluoride (SF_6).

Methods

Study areas

In Korea, the direct landfilling of raw food wastes was banned in 2005 in order to mitigate the shortage of landfill site, to protect groundwater and soil contamination, and to promote recycling of food wastes as an available resource [14,15]. These efforts resulted in a highly effective recycling rate in food wastes (e.g., over 94% of food waste recycled in the nation in 2006). Approximately 13,372 tonnes of food waste was generated per day as of 2006 in Korea, 261 tonnes of which (2% of daily generation) was landfilled; 509 tonnes (4%), incinerated; 12,603 tonnes (94%), recycled (Table 1). The study area, Jungnang District, is located in Northeastern Seoul. It consists of a residential area (57.8%), green area (40.4%), commercial area (1.7%), and semi-industrial area (0.1%). The district, which had 174,475 households (421,422 residents) in 2012, generated 81 tonnes of food waste from single houses (9.8%), town houses (34.1%), apartments (35.3%), and restaurants (13.6%) per day as of 2008, 65.5 tonnes of which (81% of daily generation) were recycled for animal feed and 15 tonnes (19%) for compost.

Statistical data showed that the treatment methods of food wastes in Korea have been concentrated on feed manufacturing for animals and composting. These facilities for treating food wastes by these methods have been usually located in a rural area such as the Gyeonggi province; therefore, the food waste generated in the metropolitan area such as in Seoul has to be generally passed to other districts and has been causing problems for transportation, odor, hygiene concerns, and adverse environmental impacts. It is recommended that food waste treatment and disposals should be covered within their own district. It also requires the use of the most effective treatment system that minimizes environmental risks.

Modeling approach

In this study, the function was defined as food waste disposal, and the functional unit was defined as 1 tonne of food waste from households for each treatment option. For data calculation, the reference flow was defined as 1 tonne of food waste.

In the present study, the system boundary for LCA describes the time from initial food waste generation at the household to its final disposal. To calculate GWP of food waste treatment options, five stages were defined and investigated; they are separate discharge, separate collection, transportation, treatment, and resource/energy production of disposal from food waste generation to final disposal. Food wastes were collected and transported to a

Table 1 Food waste treatment types and generation in Korea (tonnes/day (%))

	Year					
	2001	2002	2003	2004	2005	2006
Total amount	11,237	11,397	11,398	11,464	12,976	13,372
Landfilling	3,856 (34.3)	3,345 (29.3)	2,836 (24.9)	1,607 (14.0)	356 (2.7)	261 (2.0)
Incineration	1,003 (8.9)	922 (8.1)	844 (7.4)	541 (4.7)	516 (4.0)	509 (3.8)
Recycling sum	6,378 (56.8)	7,130 (62.6)	7,718 (67.7)	9,316 (81.3)	12,104 (93.3)	12,603 (94.2)
Animal feed	3,524 (55.3)	3,526 (49.5)	3,832 (49.6)	4,434 (47.6)	5,110 (42.2)	5,703 (45.2)
Compost	2,598 (40.7)	3,259 (45.7)	3,391 (43.9)	3,955 (42.4)	5,759 (47.6)	5,660 (44.9)
Others[a]	256 (4.0)	345 (4.8)	495 (6.4)	927 (10.0)	1,235 (10.2)	1,240 (9.8)

[a]Others include anaerobic digestion and co-digestion with sewage sludge. Adapted from the Ministry of Environment (South Korea) [14].

treatment facility. An avoided impact analysis was applied to energy and resource recovery. Electricity and steam can be produced by converting waste to captured biogas; the steam was used for warming the digester. The produced steam was excluded because energy usage such as electricity or fuel for processes was already not counted as the same amount as the steam from biogas. The decision rules for the inclusion of input and output materials into the system boundary were cumulative weight, energy, and relevance to the environmental aspects, all suggested by ISO/TR 14049 [16]. The decision rule applied was to include up to 99% of the total product weight in the system boundary. Energy and hazardous substances were all included into the system boundary regardless of their quantities.

The environmental impacts of each stage were analyzed using LCA methodology and an indicator model. The life cycle inventory tool, Total 3.0, developed by Korea Eco-Products Institute (Seoul, South Korea), was used.

Scenario construction and process description

Three different scenarios of food waste disposal were demonstrated. Each system was to treat food wastes to stabilize and sterilize the final goal of waste reduction and disposal by environment-friendly methods. Therefore, in the study, all scenarios had a consideration on final disposal. The scenarios were defined as follows:

- *Scenario 1 anaerobic digestion*. Biogas was produced by hydrolysis, acidification, and methane fermentation.
- *Scenario 2 co-digestion with sewage sludge*. Pretreated food waste was anaerobically digested with primary sludge in the STP.
- *Scenario 3 dryer-incineration*. Food wastes were dried by a machine after discharging at a household kitchen and moved to a facility for energy recovery.

Scenarios 1 and 2 were presented as potential waste management methods that are not commonly used in Korea but could meet current demands for renewable energy recovery from biomass and GHG reduction. Scenario 3 may be a possible option. It has been reported that various garbage dryers have been used in households in Korea as well as in many countries.

Anaerobic digestion

Food wastes were injected to the input hopper for pretreatment after weighing. Vinyl, animal born, and debris were sorted for the shredding process. The next step was that the pretreated food wastes were supplied to an anaerobic digester. Captured biogas was converted to steam. This steam was used for warming the digester. About 75%, 5%, 10%, and 10% of the input mass output were wastewater, screenings, final sludge, and biogas, respectively. This final

sludge was used as an ingredient in manufacturing a fertilizer [17]. Produced biogas was burnt in engines that turn generators to make electricity. About 35% of the input energy outputs as electric energy, and the rest of the heat from the engine cooling water was used to warm the digesters. The produced steam was recycled within the system, and electricity was sold at the national power exchange (Figure 1).

Co-digestion with sludge

The process was classified with two subunit processes, pretreatment and co-digestion. Food wastes should be pretreated by sorting vinyl and animal born before injection to an anaerobic digester in the STP to promote organic decomposition and stabilization. Co-digestion with food wastes took advantage of the increasing biogas due to high concentrated organic input in the STP. Food wastes could be supported as a carbon source when advanced treatment technologies are applied to a plant. Food wastes were injected to a hopper and moved to a centrifuge through shredding and sorting processes. The cakes generated from the centrifuge were moved to a landfill site for final disposal, and other screenings from sorting processes were moved to a resource recovery facility for incineration. Pretreated food wastes were highly rich organic liquids that looked like pulp because screenings and centrifuged cakes were removed. The liquids were delivered to an anaerobic digester in the STP; it was mixed with primary sewer sludge and was stabilized. Biogas was produced through hydrolysis, acidification, and methane fermentation processes (Figure 2).
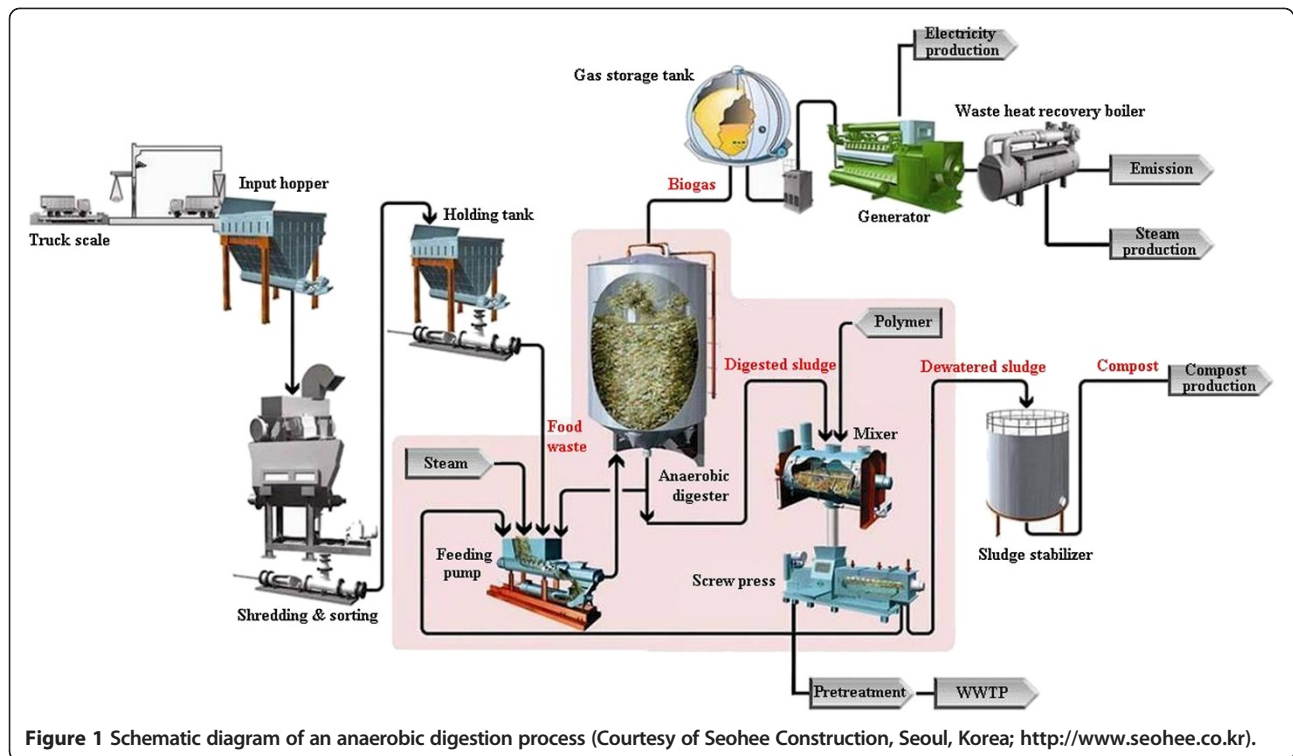
Dryer-incineration

After the moisture contained in food wastes was removed using a dryer, the dried food wastes were discharged with MSW. MSW including dried food wastes were collected by a garbage truck and stored at a transfer station. The wastes were moved to a resource recovery facility for incineration and burnt at 850°C to approximately 1,100°C. The high-temperature gas produced steam which operated a steam turbine and then produced electricity. The steam was passed to a heat exchanger, and it supported the residential area's hot water for room heating. Air emissions and wastewater were discharged during the process. Wastewater was moved to the STP after pretreatment. Fly ash and bottom ash were moved to a landfill for final disposal.
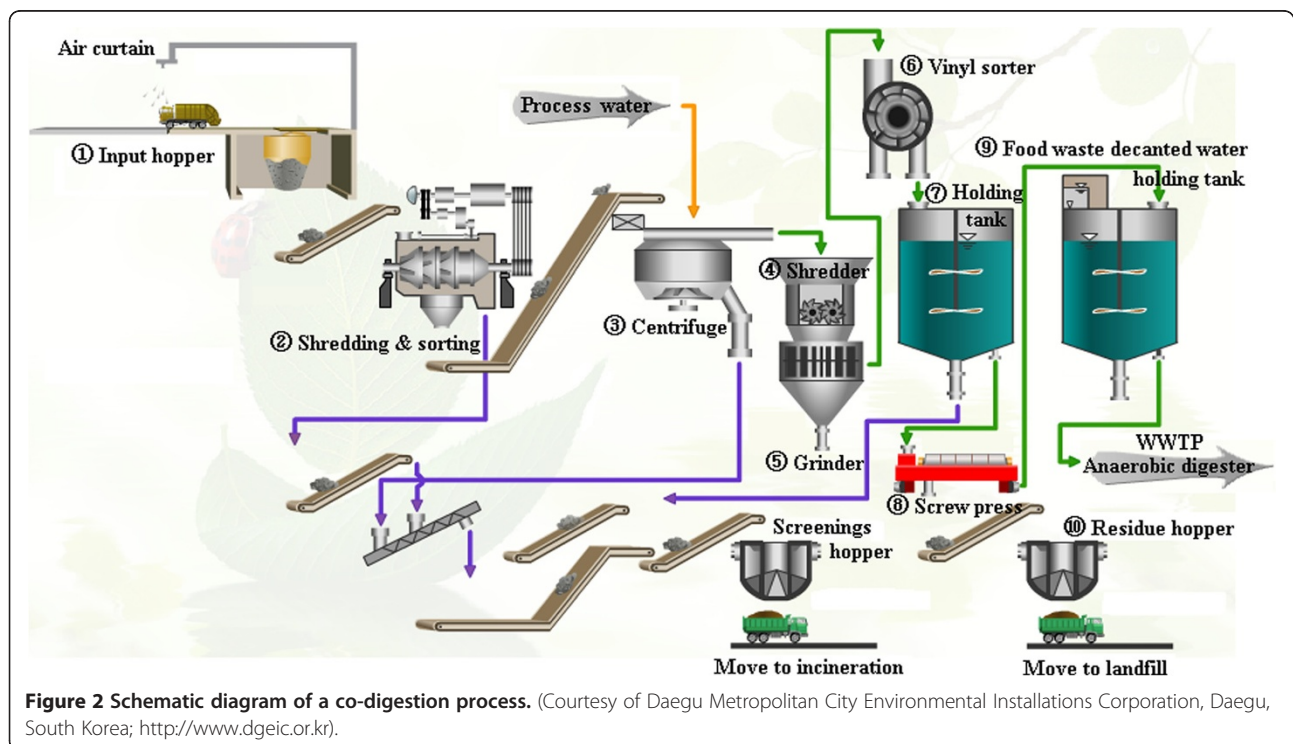
Allocation and avoided impact approach

ISO 14041 mention that allocation should be applied following these stepwise procedure [18,19]:

Step 1 Whenever possible, allocation should be avoided by dividing the unit process to be allocated into two or more subprocesses and collecting the input and output

Figure 1 Schematic diagram of an anaerobic digestion process (Courtesy of Seohee Construction, Seoul, Korea; http://www.seohee.co.kr).

data related to these subprocesses or by expanding the product system to include the additional functions related to the coproducts.

Step 2 Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them.

Step 3 Where physical relationship alone cannot be established or used as the basis for allocation, the

Figure 2 Schematic diagram of a co-digestion process. (Courtesy of Daegu Metropolitan City Environmental Installations Corporation, Daegu, South Korea; http://www.dgeic.or.kr).

inputs should be allocated between the products and functions in a way which reflects other relationships between them (i.e., economic value of the products).

An expanded system boundary was applied for the comparison of different by-products of each scenario. The most appropriate method for the quantification of environmental credit (or benefit) that resulted from the recycling of by-products is the system expansion method as shown in Figure 3. By-products generated from the product manufacturing process can be used as raw materials for other product systems, resulting in reduction of the use of virgin raw materials in the other product systems. It has been generally accepted that the use of recycled materials is environmentally preferable to that of virgin raw materials. This is because the environmental loads associated with the processing of recycled materials are less than those associated with the extraction and processing of virgin raw materials [20]. In the anaerobic digestion scenario, produced biogas primarily used to warm a digester then to a surplus biogas converts to electric energy. In the co-digestion scenario, produced biogas is completely used to warm a digester. Therefore, the system had no surplus energy to use outside of the system boundary. In the dryer-incineration scenario, produced heat energy converted to steam is completely used for residential room heating. An environmental credit which resulted from recycling of food wastes could be analyzed and quantified by avoided impact analysis. Therefore, these food waste recycling systems could reduce negative impacts to the environment as compared with new commercial product manufacturing.
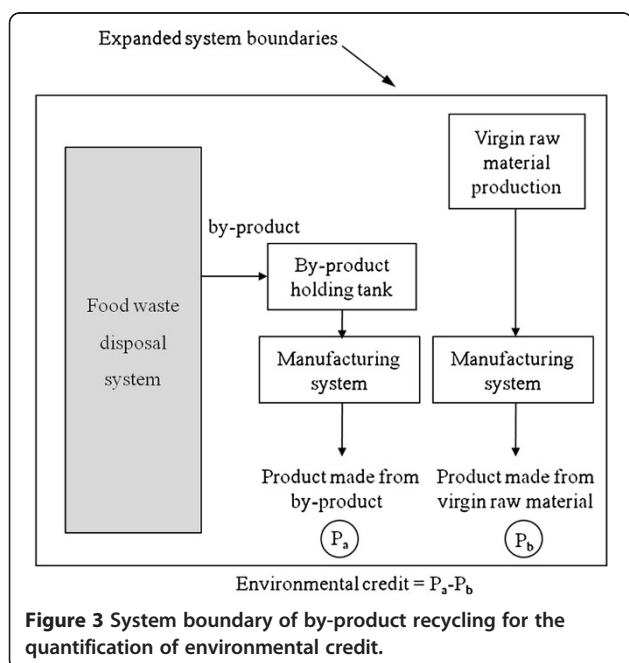

Figure 3 System boundary of by-product recycling for the quantification of environmental credit.

Assumptions

There were some assumptions:

Most of the discharged sludge from the STP have been dumped to the ocean. However, it should be restricted to protect the ocean's environment. An environmental impact was simulated under the assumption that sludge was managed by incineration.

Biosolids from anaerobic digestion was to be a raw material for the manufacturing of a fertilizer.

Screenings were delivered to a landfill for the final disposal.

Final wastes were burnt at the Nowon Energy Recovery Facility in case of incineration or buried at the Sudokwon landfill site in case of landfilling.

When additives such as coagulants and chemicals for pH adjusting were added, the distance for transportation was 8 km, which is based on a study that over 10 km of distance was not cost-effective [21].
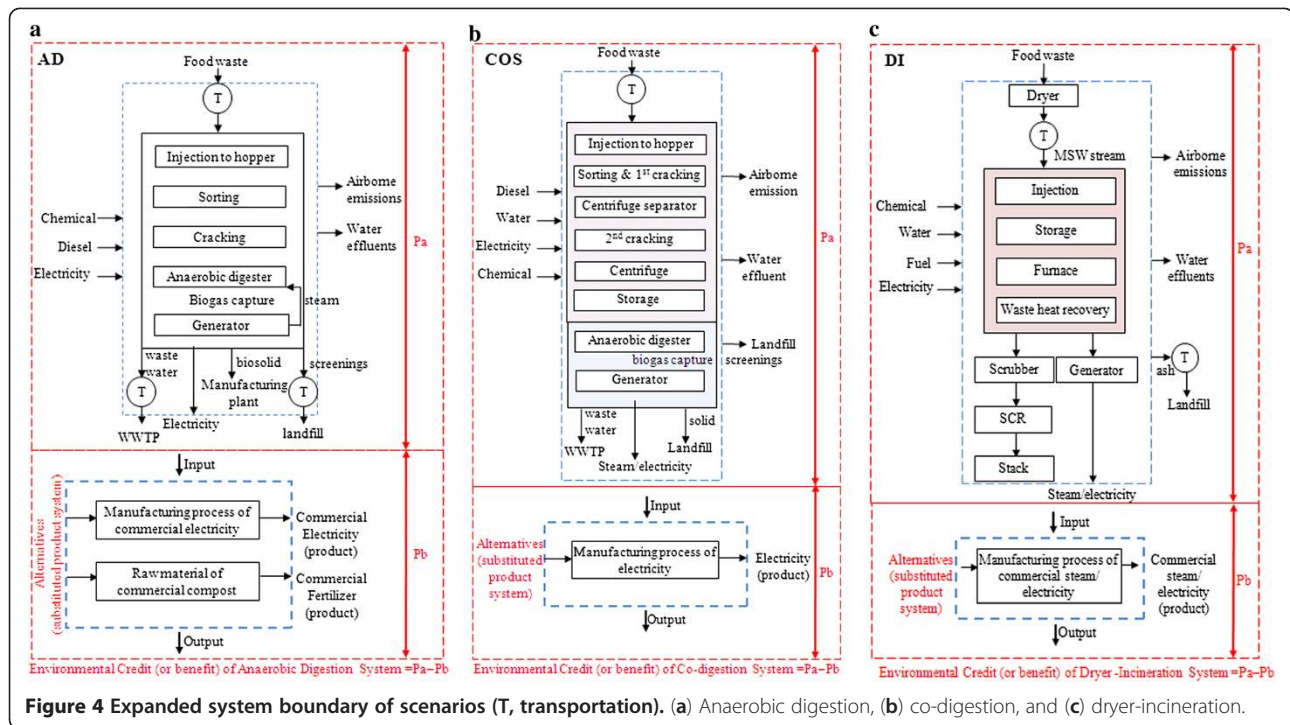
Results and discussion
Data collection

Data quality should be characterized by quantitative and qualitative aspects. Data collection was based on site inspections. In the present study, time-related coverage was from 2005 to 2009; however, plant data were collected with the age of data within the latest year, specifically 2008. Literature data were collected with the time scope within the last 5 years. Data were collected by plant survey at a facility in Sainggok, Busan City for anaerobic digestion, in Shincheon, Daegu City for co-digestion, and in Nowon, Seoul metropolitan for dryer-incineration to satisfy the expanded system boundaries of each scenario as shown in Figure 4. Up- and downstream databases, which were connected with technosphere, were taken by the Ministry of the Environment and the Ministry of the Knowledge Economy, Korea. In the case of non-existing data, data inventories were directly constructed with site inspection data, or overseas inventory supported by SimaPro 7.1 was used. The analysis was conducted in accordance with the methods stipulated in ISO 14040 [22,23].

Life cycle inventory analysis
Discharge stage

Dryer-incineration. Food wastes were dried using a garbage dryer at the discharge stage by a discharger. Two types of the popular garbage dryers which dominated at the market share were installed in ten of the sample houses and were tested by residents. Under the data from the user surveys, 75.9% weight reduction in efficiency resulted from one operation on 1 day and in the next, which is 3.35 min of continuous activity. Electricity consumption was averaged at 648.884 kW h/tonne of

Figure 4 Expanded system boundary of scenarios (T, transportation). (**a**) Anaerobic digestion, (**b**) co-digestion, and (**c**) dryer-incineration.

food waste using both stirring warm air drying and warm air circulation drying.

Separate collection stage

Food wastes were kerbside collected by a 5-tonne-capacity garbage truck and transported to a transfer station. The distance for collection depended on the collection systems. However, the round-trip distance was accepted, and the average distance of 94.4 km was directly measured in Jungnang District, the study region. Fuel efficiency was 4.8 km/L, and the load was 5 tonnes/truck. In the dryer-incineration scenario, about 0.24 tonne of dried food waste was collected.

Transportation stage

The study area, Jungnang, has had its own transfer station. Food wastes were transported from a transfer station to each facility by an 11-tonne truck. The distances from the transfer station to each facility were as follows: around 5.21 km to the anaerobic digestion facility for the anaerobic digestion scenario and around 3.97 km to the STP for the co-digestion scenario. In the case of dryer-incineration scenario, around 8.42 km was the calculated distance to the Nowon energy recovery facility; however, the weight of the dried food wastes was around 0.24 tonne.

Treatment stage

- *Anaerobic digestion.* The target facility treated 200 tonnes of food waste by anaerobic digestion per day.

Approximately 14.29 tonnes of biogas and 22 tonnes of biosolids were produced for a day. About 40 tonnes of processed water was recycled. Around 200 tonnes of wastewater and 21.2 tonnes of screenings were produced. The quality of wastewater was 5,440 mg/L of BOD, 4,520 mg/L of SS, 2,400 mg/L of T-N, and 19 mg/L of T-P. The wastewater was pretreated before moving to the STP. For this process, 13,645 kW h of electricity usage was required. Produced biogas was converted to 48,735 kW h of electricity and 40.79 tonnes of steam per day. Steam was used to warm the digester. Electricity typically covered 13,645 kW h of daily usage for the process operation, and a surplus of 35,089 kW h was sold at Korea Power Exchange. Air emissions from the combustion of generated biogas were calculated by IPCC emission factors. Produced CO_2 was not counted on GHG because it had a biogenic origin. It was investigated that 242.64 kW h of electricity, 4,280,000 kcal/h of steam, and 0.11 tonne of biosolids were produced from 1 tonne of food waste. In this study, surplus electricity and the biosolids were analyzed by an avoided impact approach. The gate-to-gate data of the scenario is shown in Table 2.

- *Co-digestion.* The selected facility treated about 200 tonnes of food waste per day with mixing sewage sludge in the STP. The co-digestion process was divided into two major sections, pretreatment and co-digestion. The pretreatment covered sorting,

Table 2 Gate-to-gate data for the scenarios at treatment stage

		Materials	Anaerobic digestion	Co-digestion	Dryer-incineration	Unit
Input	Materials	Food waste	1.00E + 03	1.00E + 03	2.41E + 02	kg
		Chemicals	2.70E + 02	3.11E + 01	1.53E + 00	kg
		Process water	-	-	1.08E + 01	kg
	Energy	Diesel	-	-	1.12E − 01	kg
		Liquefied natural gas	-	-	6.22E + 01	MJ
		Electricity	6.82E + 01	3.68E + 01	7.91E + 00	kW h
Output	By-products	Electricity	2.43E + 02	-	-	kW h
		Biosolids	1.10E + 02	-	-	kg
		Waste heat recovery	-	-	2.16E + 00	Gcal
		Wastewater/leachate	1.00E + 03	-	3.25E + 01	kg
		Sludge	-	1.41E + 02	-	kg
		Screenings	1.10E + 02	3.59E + 02	-	kg
		Fly ash	-	-	3.81E − 01	kg
		Bottom ash	-	-	2.49E + 00	kg
	Air emission	CO_2	-	-	7.66E + 02	kg
		CH_4	5.48E − 02	6.37E − 03	4.70E − 02	kg
		N_2O	7.32E − 03	8.50E − 04	-	kg
		NO_x	1.83E − 01	2.12E − 02	6.25E − 01	kg
		CO	1.83E + 00	2.12E − 01	5.69E − 01	kg
		MVOC	9.12E − 02	1.06E − 02	-	kg
		Particles	-	-	6.35E − 02	kg
		Dioxin	-	-	2.63E − 06	kg

shredding, and dewatering. Pretreated food wastes, which were in pulp status, were injected to an anaerobic digester with primary sewage sludge. On the basis of plant data from July 2007 to June,2008, an average of 193 tonnes of food waste per day was pretreated, and then 293 m^3 of pulp-phase food waste and 1,206 m^3 of sewage sludge per day were co-digested by anaerobic digestion. Finally, 11,150 m^3 of biogas per day was produced. An average of 3,700 kW h of electricity per day was required. Around 213 tonnes of processed water per day was needed to move the pulp-phase pretreated food waste easily to the anaerobic digester. Approximately 77 tonnes (around 40% of the daily treated food waste) of screenings and dewatered cakes per day were sorted and finally landfilled. In this system, pretreated food wastes (flow rate at 250 m^3/day, volatile solid (VS) 39 kg/L) and the first sludge from a primary sedimentation tank (flow rate 1,300 m^3/day, VS 12.9 g/L) were mixed in the anaerobic digester. Sewage sludge and pretreated food wastes were injected to the digester in a ratio of 5:1, and the ratio of volatile solid concentration of sludge and food wastes was 1:3. Biogas production in 2006 was 7,236 m^3 from sewage sludge alone; this

increased to 9,745 and 9,559 m^3 of biogas in 2007 and 2008, respectively, when co-digestion with food wastes was introduced. It was represented that co-digestion with the food waste system produced around 34% of biogas more than sludge digestion alone.

○ *Allocation for biogas quantification.* Biogas production was calculated by allocation. In 2008, a daily increase, around 2,323 m^3, was produced from 196 tonnes of food waste; therefore, it was estimated that 11.85 m^3 of biogas was produced from 1 tonne of food waste. It was 13.32 m^3 in 2007 (Table 3). It was converted to 8.92 kg of weight based from the

Table 3 Biogas production from the co-digestion

Year	Total biogas production (m^3/day)	Food waste input (kg/day)	Biogas production from food waste (m^3/kg)	Note
2006	7.24E + 03	0.00E + 00	0.00E + 00	Sewage sludge only
2007	9.75E + 03	1.88E + 05	1.33E − 02	Sewage sludge plus food wastes
2008	9.56E + 03	1.96E + 05	1.19E − 02	Sewage sludge plus food wastes

average value of 12.59 m^3. CO_2-eq of 186 kg was generated as GHG from co-digestion treatment process. GHG production from the combustion of biogas, which was generated for this process, was calculated using IPCC emission factors. If generated CO_2 was a biogenic origin, then this CO_2 was excluded on the counted GHG.

○ Allocation for electricity quantification. Electricity usage was calculated by allocation. According to the visiting surveys at selected STPs, the station for pumping to a grit chamber, facility operation (including settler and clarifier), and aerator operation needed 27.75%, 8.86%, and 37.46% of total electricity usage, respectively. In the case of the sludge treatment process, dewatering, sludge thickening, and deodorization needed 19.89%, 4.54%, and 1.50% of electricity, respectively. Therefore, 74% and 26% of electricity were used for sewage treatment process and sludge treatment process, respectively. Another selected STP showed that 50% of electricity was consumed for aeration, and 32% and 9% of electricity was consumed by the facility operation and pump station, respectively. Only 8% of electricity was used for anaerobic digestion. Therefore, it was assumed that an average of 17,511 kW h (17%) was used for sludge treatment by anaerobic digestion. Allocation was followed by flux rate, therefore, it was estimated that 3,502 kW h, which was one fifth of electricity, was consumed for anaerobic digestion per day. The facility treated around 196 tonnes of food waste a day; therefore, it was assumed that daily electricity for anaerobic digestion per 1 tonne of food waste was 17.87 kW h. In conclusion, 18.88 kW h, which was already calculated for pretreatment of 1 tonne of food waste, and 17.87 kW h, which was calculated by allocation here for anaerobic digestion, were counted for this scenario. The sum of two electric values, 36.75 kW h, was estimated as electricity usage for 1 tonne of food waste treatment by co-digestion.

We calculated that 36.75 kW h of electricity was used and 8.92 kg of biogas was produced for the treatment of 1 tonne of food waste by allocation. Steam, which was converted from the captured biogas, was used for digester warming. The environmental impact of the recycled processed water and steam was not considered because it was already counted on the system. It was estimated that 141 kg of sludge was discharged from 1 tonne of food waste. The gate-to-gate data is shown in Table 2.

- Dryer-incineration. Reduction efficiency was 75.9% of food waste; therefore, the water containing food

wastes after drying with the use of a garbage dryer reduced in weight from 1 to 0.24 tonne (Table 2). Volume was also reduced; however, ultimate constituents were not changed. Produced fly ash and bottom ash were transported to the Sudolwon landfill site for final disposal. As the ash from complete incineration contained no organic carbon when it arrived at the landfill, the burial of ash would generate no landfill gas (LFG). Carbon was not completely removed by incineration, but it can be assumed that the landfill of incinerator ash resulted in no LFG emissions [24]. Therefore, we estimated that GHG from the ash at the landfill was not produced; however, GHG by transportation was added. Around 364 kg of CO_2, 7.99 kg of CH_4, and 2.75 kg of N_2O were produced. The produced CO_2 was non-biogenic and was produced from energy consumption. However, CO_2 by incineration of food waste was not counted as GHG because it was biogenic in origin. The caloric value (wet based) of 1 tonne of dried food waste was 2.92 Gcal, and energy recovery would be 9,047 MJ if the average recovery rate of 74% was applied (Table 4). Therefore, it was estimated that around 657 kg of GHG was reduced.

Disposal stage

The distances of transportation from facilities to final disposal sites were calculated. It was assumed that the screenings were landfilled and the sludge was incinerated. The distances from each facility to the landfill site and resource recycling (incineration) facility were calculated respectively by GIS. One-way distances were 46 and 11 km for anaerobic digestion, 47 and 12 km for co-digestion from the facility to the landfill and resource recycling facility, respectively, and the distance was approximately 50 km between the landfill and incineration plant.

Life cycle impact assessment analysis

Characterized impact on the global warming impact category was assessed using GWP for 100 years [25].

Anaerobic digestion

The indicator, GWP, represented that the treatment and disposal stages mainly contributed to the environment.

Table 4 Energy recovery rate of the dryer-incineration

Factor	Value	Recovery rate
Low-heating value of dried food waste (wb[a])	2.92 Gcal/tonne	74%
Energy recovery	9,047 MJ[b]	
GHG reduction	657 kg CO_2/tonne	

[a]Wet based; [b]1 Gcal = 4186.8 MJ.

Directly discharged CO_2 for digestion was biogenic in origin; therefore, it was not counted as GHG. In addition, produced methane was captured. However, the treatment stage still contributed to GWP the most because chemicals and electricity usage were sources of GHG. Screenings were finally landfilled, and wastewater was treated chemically or biologically. These final disposals also contributed to global warming. This anaerobic digestion system treated 1 tonne of food waste and produced 0.07 tonne of biogas. The biogas was converted to 244 kW h of electricity and 204 kg of steam. About 68.23 kW h of electricity was primarily used for the facility operation. Surplus electricity of 175 kW h was sold at Korea Power Exchange. Produced steam was used for warming a digester. About 110 kg of biosolids was also produced. It was sold as a raw material of compost. For this scenario, 211 kg of CO_2-eq of GHG were discharged from 1 tonne of food waste. Around 8.8, 0.7, 131, and 70.1 kg of CO_2-eq of GHG were produced in the collection, transportation, treatment, and disposal stages, respectively (Table 5).

Co-digestion

The indicator, GWP, represented that disposal stages mainly contributed to the environment. Screenings, which were produced for the pretreatment process, were disposed by landfilling. LFG was the major reason of global warming in the co-digestion scenario. For this scenario, 259 kg of CO_2-eq of GHG were discharge from 1 tonne of food waste. Around 8.8, 0.5, 37.7, and 212 kg of CO_2-eq of GHG were produced in the collection, transportation, treatment, and disposal stages, respectively (Table 5). Landfilling of the screenings was contributed to GWP the most in this scenario.

Dryer-incineration

Electricity was consumed for the garbage dryer operation. Produced CO_2 in the incineration process was biogenic in origin; therefore, it was excluded from the GHG counting. In addition, combusted waste heat was recovered and converted to steam. This system treated 1 tonne of food waste and produced 2.16 Gcal of heat energy. It was sold and used in the residential area for room heating with hot water heating. For this scenario, 342 kg of CO_2-eq of GHG were discharged from 1 tonne of food waste. Around 321, 8.8, 1.1, 10.3, and 0.7 kg of CO_2-eq of GHG were produced in the discharge, collection, transportation, treatment, and disposal stages, respectively (Table 5).

Avoided impact analysis

Avoided impact was analyzed in order to calculate efficiencies of GHG reduction relevant to alternatives. The commercial production of steam and electricity was analyzed by LCA. The result showed that 0.04 and 0.50 kg of CO_2-eq of GHG were produced when 1 MJ of steam and 1 kW h of electricity were manufactured, respectively. About 178 kg of CO_2-eq by anaerobic

Table 5 GHG emissions (kg CO₂-eq/tonne) at each stage

		Anaerobic digestion	Co-digestion	Dryer-incineration
Discharge (household)		0.00E + 00	0.00E + 00	3.21E + 02
Electricity		-	-	3.21 E + 02
Collection (diesel)		8.81E + 00	8.81E + 00	8.81E + 00
Transportation To Facility (diesel)		6.71E − 01	5.10E − 01	1.08E + 00
Treatment process		1.32E + 02	3.77E + 01	1.03E + 01
Direct GHG emission		3.42E + 00	3.97E − 01	4.90E + 00
Electricity		3.38E + 01	1.82E + 01	3.92E + 00
LNG		-	-	5.99E − 01
Water		-	-	1.23E − 03
Diesel		-	-	4.30E − 02
Additive	Transportation	1.87E − 02	1.87E − 02	1.15E − 03
	Chemical	9.37E + 01	1.91E + 01	8.38E − 01
Final disposal		7.01E + 01	2.12E + 02	6.83E − 01
Transportation to disposal site		9.49E − 01	3.14E + 00	3.30E − 01
Electricity		1.34E + 00	-	-
Solid		6.40E + 01	2.09E + 02	-
Wastewater		3.83E + 00	-	3.53E − 01
Total		2.11E + 02	2.59E + 02	3.42 E + 02

Table 6 Alternative effects of scenarios

Scenario	1-tonne food waste treatment options			Avoided impact		
	By-product		GWP (Pa)	CO$_2$ reduction (Pb)	Environmental credit (Pa-Pb)	Unit
Anaerobic digestion	Electricity	1.74E + 02(kWh)	2.11E + 02	8.46E + 01	3.32E + 01	kg
	Biosolids	1.10E − 01(tonne)		9.32E + 01		
Co-digestion	NA	NA	2.59E + 02	NA	NA	-
Dryer-incineration	Waste heat	9.05E + 03(MJ)	3.42E + 02	6.57E + 02	−3.15E + 02	kg

digestion and 657 kg of CO$_2$-eq by dryer-incineration from 1 tonne of food waste, respectively, were calculated by avoided impact analysis. In the case of dryer-incineration, GHG was reduced by waste heat recovery; however, GWP was still high through the full stages. It was because a garbage dryer operation required electricity usage.

This comparison of three different food waste disposal scenarios found that the GWP of each scenario before the offset of generated electricity is around 211 kg of CO$_2$-eq for anaerobic digestion, 259 kg of CO$_2$-eq for co-digestion, and 342 kg of CO$_2$-eq for dryer-incineration from 1 tonne of food waste, respectively, all based on the wet weight. GWP of dryer-incineration in the treatment stage was low because CO$_2$ production from incineration was biogenic in origin; however, GWP in the discharge stage was the highest because electricity usage for a waste dryer operation in the discharge stage contributed to GWP. Anaerobic digestion, co-digestion, and dryer-incineration scenarios were higher in GWP in that order.

Around 110 kg of biosolids, 244 kW h of electricity, and 0.2 tonne of steam were produced by the anaerobic digestion scenario. Biosolids were used as a raw material in the composting industry. Steam was not included in analyzing the by-product because it was recycled in the system boundary. Around 70 kW h of produced electricity was used for facility operation; therefore, 174 kW h of electricity could be sold in a market. Incineration scenario produced 2.16 Gcal of waste heat. It was converted to steam and supplied to residential areas. Steam of the co-digestion scenario was recycled within the system boundary. Therefore, steam production was excluded in the list of by-products. Environmental credit was 33 kg of CO$_2$-eq for anaerobic digestion and –315 kg of CO$_2$-eq for dryer-incineration from 1 tonne of food waste, respectively (Table 6).

In the present study, the indicator, GWP, was used for environmental impact analysis. We analyzed six impact categories, ADP, AP, EP, GWP, ODP, and POCP for the scenarios as shown in Table 7. The results show that GWPs of all scenarios affect the environment the most although POCP of dryer-incineration is high.

We analyzed the B/C ratio of the scenarios and found that it was 0.11 for anaerobic digestion and 0.26 for dryer-incineration in the previous research [26]. We

Table 7 Environmental impact for each impact category of scenarios

	Characterization (a)				Normalization reference (b)		Normalized result (a/b)		
	AD	COS	DI	Unit	Factor	Unit	AD	COS	DI
ADP	1.05	2.80	4.02	1/year	24.9	kg/person-years^2	4.22	1.12	1.61
	E + 00	E − 01	E − 01				E − 02	E − 02	E − 02
AP	5.56	1.84	3.32	kg of SO$_2$-eq/kg	39.8	kg of SO$_2$-eq/person-years	1.40	4.61	8.33
	E − 01	E − 01	E − 01				E − 02	E − 03	E − 03
EP	1.79	2.92	1.06	kg of PO$_4^{3-}$-eq/kg	13.1	kg of PO$_4^{3-}$-eq/person-years	1.37	2.23	8.08
	E + 00	E − 02	E − 01				E − 01	E − 03	E − 03
GWP	2.12	2.60	3.42	kg of CO$_2$-eq/kg	5530	kg of CO$_2$-eq/person-years	3.83	4.70	6.18
	E + 03	E + 03	E + 03				E − 01	E − 01	E − 01
ODP	1.28	4.72	1.04	kg of CFC11-eq/kg	0.0407	kg of CFC-eq/person-years	3.10	1.20	2.60
	E − 05	E − 06	E − 05				E − 04	E − 04	E − 04
POCP	2.23	1.01	1.01	kg of C$_2$H$_4$-eq/kg	10.3	kg of C$_2$H$_4$-eq/person-years	2.16	9.81	9.76
	E − 01	E − 01	E + 03				E − 02	E − 03	E + 01

AD, anaerobic digestion; COS, co-digestion with sludge; DI, dryer-incineration; ADP, abiotic resource depletion potentials; AP, acidification potentials; EP, eutrophication potentials; GWP, global warming potentials; ODP, ozone depletion potentials; POCP, photochemical oxidant creation potentials.

could not find it for co-digestion because the by-product of co-digestion was recycled within the system boundary.

Conclusions

This study evaluated three food waste disposal systems: anaerobic digestion, co-digestion, and incineration of dried food waste, using LCA from the perspective of global warming and energy/resource recovery. Since landfilling of food wastes was banned in 2005, animal feeding and composting have been the major practice for treating them, and anaerobic digestion and co-digestion were the minor ones. Incineration is an available method for energy recovery from municipal solid wastes. Incineration of raw food waste has been practiced for increasing the heating value in a few local governments in Korea; however, it provokes a lot of controversy because of much moisture and salinity constituent. The three scenarios were evaluated though they are not major disposal methods in Korea because we concentrated in energy recovery from food wastes to suggest alternatives.

GWP, which is an indicator to evaluate environmental impact, was acquired in five stages: discharge, collection, transportation, treatment, and disposal stages. We found that the GWPs were estimated to be 211 kg of CO_2-eq for anaerobic digestion, 259 kg of CO_2-eq for co-digestion, and 342 kg of CO_2-eq for dryer-incineration from 1 tonne of food waste.

From analyzing the by-products from each scenario, 174 kW h of electricity and 110 kg of raw materials for compost from anaerobic digestion and 9,050 MJ of heat from dryer-incineration were produced. An avoided impact showed that by-products from 1 tonne of food waste could reduce GHG; for example, 178 kg of CO_2-eq by anaerobic digestion and 657 kg of CO_2-eq by incineration might offset the global warming potential of each system under the assumption that the by-products were completely utilized. Therefore, the environmental credit of the three options based on the wet weight of food waste was found to be 33 kg of CO_2-eq for anaerobic digestion and –315 kg of CO_2-eq for dryer-incineration from 1 tonne of food waste by electricity, thermal energy generated, and primary materials avoided. We found that dryer-incineration is the best available alternative for producing renewable energy in Korea. In the case of the co-digestion scenario, future studies need to increase biogas production. In the dryer-incineration scenario, it is available to acquire heat energy although energy consumption is high at the discharge stage. It could be one of the practical treatment methods under reducing energy requirements.

The limitations and future studies suggested in this study are as follows: Jungnang District in Seoul City, one of the facilities currently operated for each scenario in the study area, was selected and evaluated; however, the data from the selected facilities may not represent national or global trends.

Authors' contributions
MHK carried out the study plan, analyzed environmental impacts, and drafted the manuscript. HBS collected data and drafted the manuscript, tables, and figures. YS participated in the literature review, reviewed the manuscript, and corrected an error. ITJ developed the methodology and participated in the analysis of the results. JWK participated in the analysis of the results. All authors read and approved the final manuscript.

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