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Greenhouse Gas Emissions and Cost Analyses for the Treatment Options of Food Waste and Human Excrement

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Abstract

This study suggested environmental and economic evaluations by developing a scenario according to the various treatment options of food waste in Korea. In particular, the study evaluated the possibility about the combined treatment of food waste and human excrement after using food waste disposers (FWDs). The scenario including only composting (133 kg CO_2 equiv./ton-household organic waste) or only FWDs (125 kg CO_2 equiv./ton-household organic waste) was superior to the other scenarios in the environmental aspect and the scenario including only composting (101 USD/ton-household organic waste) was superior to the other scenarios in the economic aspect. However, the study discovered that 52% of greenhouse gas emission was reduced when sewage pretreatment was conducted in houses after using FWDs and also when biogas was collected on site and utilized in the private power station. Furthermore, the energy saving effect due to recovery of biogas has found to be larger in the environment aspect than in the economic aspect.

Keywords

Food Waste Disposer, Food Waste Drying Machine, Composting, Biogasification, Automatic Vacuum Waste Collection System

1. Introduction

Food waste and human excrement, *i.e.*, human biological waste is household organic waste which is highly valued as the production of biomass such as biosolids, biogasification, and bioethanol [1]-[4]. In Korea, 97.1% of

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the total food waste generation has been separately collected food waste from municipal solid waste (MSW) and recycled to animal feed and compost since 2005 [5]. Due to food waste separation from MSW, MSW composition in landfill sites and incineration plants has been changed. As a result, the efficiency of waste to energy in landfill sites and incineration plants was differed by changing of biodegradable composition and lower heating value (LHV), respectively. The existing study has reported that the LHV of municipal solid waste increases by 6.4% when 32.8% of the household food waste used the food waste disposers (FWDs). In that report, the ratio of household combustible waste of the total combustible waste was 58.6%, the ratio of household food waste of the household combustible waste was 44.0% [6].

Since food waste was collected separately from the municipal solid waste, unsanitary problems, including unpleasant odors, germs, insects, and feeling of aversion from curbside waste, have increased. Due to these problems, many households tend to install food waste disposal units (FWDs or food waste decomposers by using drying system) such that food waste can be treated before it is taken out [7]. Recently, FWDs are supplied to large scale apartment complexes via the built-in system in general. However, the applicability of these units is not high due to the burden of additional electricity and water demands as well as the early purchase cost [8].

Figure 1 shows sewer systems in Seoul, Korea. The FWDs give effects for wastewater loadings and biogas production in the public wastewater treatment plants (WWTPs) [9]-[11].

Seoul has already carried out pilot studies in order to treat food waste in the public WWTPs. The studies were conducted by introducing domestic in-sink FWDs to 447 households in apartment houses with the sewage pretreatment facilities and 538 households in apartment houses with the sewage pretreatment facilities combined with human excrement. The result of the pilot studies has found that the combined treatment of food waste with human excrement lowers the effluent biological oxidation demand (BOD) concentration (food waste: 1055.1 mg/L, food waste and human excrement mixture: 804.1 mg/L), and increases SS concentration (respectively, 905.7 mg/L, 1564.4 mg/L) and n-Hexane concentration (respectively, 195.9 mg/L, 240.5 mg/L), more than the food waste treatment [12] [13]. If it is considered that the separate sewer system for the separated treatment of human excrement covers 14% of the sewer service area in Seoul, it needs to introduce this combined treatment of food waste with human excrement in order to reduce the environmental burden as well as to promote the convenience of the citizens.

Meanwhile, food waste has shown various environmental and economic evaluation results according to the treatment methods [14] [15]. In particular, the waste has been evaluated such that the benefit/cost (B/C) was 0.85 when domestic in-sink FWDs were used, B/C was 0.19 when the food waste was separated and put out for collection, B/C was 0.39 when the food waste was separated and put out for collection after using the food waste drying machines (FWDMs), and B/C was 0.18 when the automatic vacuum waste collection (AVWC) system was utilized [16].

Therefore, this study suggested environmental and economic evaluations about the various treatment methods of food waste and the combined treatment of food waste with human excrement after installing domestic in-sink FWDs. The environmental evaluation indicated as greenhouse gas (GHG) emissions by methane gas production and the energy equivalent and net energy consumption, which is required in the treatment. The economic

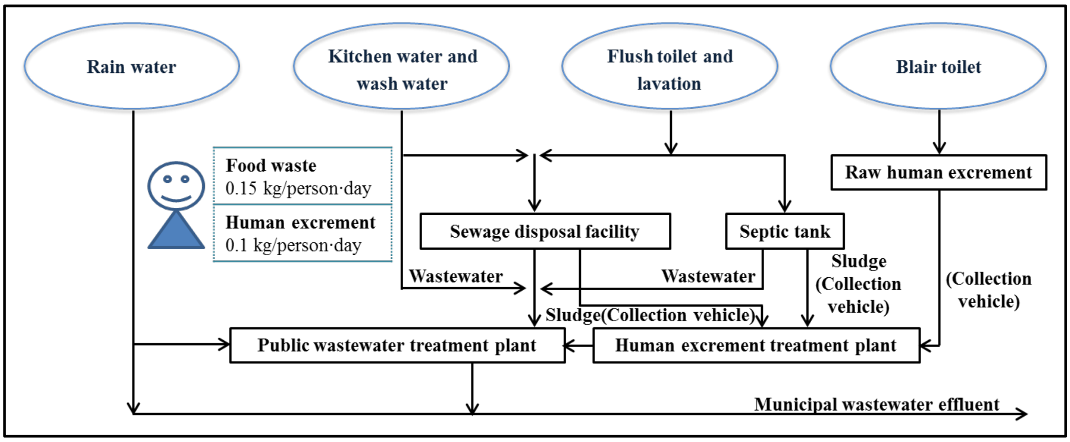

Figure 1. Sewer systems in Seoul.

evaluation is indicated as construction and operation costs, which are required in the treatment. Further, the additional social cost considering the value of domestic labor of separating and handling food waste.

2. Materials and Methods

2.1. Functional Unit and Scope

This study analyzed the properties of food waste and human excrement and the characteristics of the handling process and treatment of the household organic waste; scenarios which reflected the characteristics were developed. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. In this study, the functional unit of food waste was set to 1 ton of food waste from 6667 persons, which was based on 0.15 kg/person·day, in order to calculate the parameter. Further, the functional unit of human excrement was set to 0. 6667 ton (= 0.7 ton in the text below) from 6667 persons, because one human produces 0.1 kg of human excrement per day.

To evaluate GHG emissions and cost for the treatment options of food waste and human excrement mixture, the functional units set the quantity of human excrement per population (6667 persons) that handles 1 ton of food waste. Therefore, the functional unit for calculating parameters is 1.7 tons of household organic waste, which is the total amount of about 1 ton of food waste and 0.7 ton of human excrement. It is necessary in order to compare the scenarios of 1 ton of food waste and 0.7 ton of human excrement, which are transferred and treated in the different processes, with the scenarios of 1.7 tons of food waste and human excrement mixture, which are combined and treated in one system. The parameters based on 1 ton of food waste were calculated in order to reflect the social cost of separating and putting out the food waste for collection.

Net energy consumption (= Energy consumption in process minus energy recovery in process) was reflected in energy use. The GHG evaluation calculated the emissions from each process as well as the saved effect due to the recovery of biogas (the alternative effect based on the Korean power plants using LNG). The economic evaluation calculated the costs per each process and the saved effect due to the recovery of biogas.

As it was assumed that public sewer is the combined system and human excrement is treated in a separate sanitary treatment plant by collecting from the septic tanks, most of the scenarios did not include the use of energy, GHG emissions, and the costs according to the public wastewater treatment on human excrement. For the scenarios including the combined treatment, treated wastewater is flowed into public WWTPs; however, the part of public WWTPs of human excrement was ignored, according to the mass balance which had been applied before.

2.2. Properties and Characteristics of Household Organic Waste

2.2.1. Characteristics of Food Waste

There are big differences in the amount of food waste generation change to according to the building types or sources. Generally, the amount of generation from residential and commercial (restaurants) sectors is 0.33 kg/person/day [17], but it range from 0.12 to 0.25/kg/person/day according to the types of houses [13] [17] [18]. There are also differences in the properties of food waste according to the areas and the seasons, yet, fruits and vegetables represent the highest share of them, 55% to 75% (**Table 1**).

Food waste is treated by dividing it into public and private facilities. In the public facilities, the following occurs: animal feed (26.1%), composing (65.4%), and others (biogasification) (8.5%). Animal feed are of great importance in the private facilities because they make up more than half of total amount: animal feed 58.8%, composing 38.2%, and others 3.2%.

The result from the survey of this research reveals that 20.7% of total respondents in Seoul are now using food waste disposal units: FWDMs (9.1%); compost bins (8.0%); FWDs (2.1%); and others (1.5%). Further, 62.2% of total respondents plan to use them: FWDMs (26.0%); FWDs (24.3%); compost bins (6.8%); and others (0.4%) in the future.

2.2.2. Characteristics of Human Excrement

Human excrement is generated in blair and flush toilets in Korea. The excrement in blair toilets is referred to as raw human excrement; the one from the flush toilet is processed through the septic tank sludge. Men expel urine and feces seven times throughout the day, including one time of feces and six times of urine per day. Human excrement, when calculated, is 1 L/person/day; feces account for 0.1 L/person/day. BOD of expelled human excrement is more than 20000 mg/L and SS is 27,500 mg/L [19].

Table 1. Properties of food waste in Korea.

<table>
<tr><th rowspan="2">Composition (%)</th><th colspan="2">Korea</th><th colspan="4">Seoul</th></tr>
<tr><th>Total</th><th>Residential</th><th colspan="2">Residential</th><th colspan="2">Apartment houses</th></tr>
<tr><td>Total</td><td>100</td><td>100</td><td colspan="2">100</td><td colspan="2">100</td></tr>
<tr><td>Cereals</td><td>19.5</td><td>19.5</td><td colspan="2">15.0</td><td colspan="2">15.7</td></tr>
<tr><td>Vegetables</td><td rowspan="2">55.5</td><td rowspan="2">60.5</td><td>49.3</td><td rowspan="2">75.0</td><td>44.8</td><td rowspan="2">65.7</td></tr>
<tr><td>Fruits</td><td>25.7</td><td>20.9</td></tr>
<tr><td>Fish meats</td><td>6.6</td><td>4.4</td><td colspan="2">7.5</td><td colspan="2">6.9</td></tr>
<tr><td>Others</td><td>18.5</td><td>15.6</td><td colspan="2">2.5</td><td colspan="2">11.9</td></tr>
</table>

As shown in **Table 2**, BOD of septic tank sludge, which is carried into the Seoul human excrement treatment facilities, is higher than that of the US, as 8674 to 11343 mg/L [20] [21].

2.3. Scenario Development

A total of six scenarios were suggested by applying the applicable conditions that were most practical in Seoul City; the contents of the concrete scenarios are shown in **Table 3**. Composting was selected, except for animal feed, in the current food waste treatment methods because Korea is similar to a traditional agrarian country and thus, it can secure more stable facilities and supply and demand chain than the ones for animal feed.

This study included the options to install FWDMs or FWDs in individual houses because there were intentions to purchase FWDMs or FWDs in the previous survey. The AVWC systems, which have been recently distributed to housing complexes, were added in the transport option.

In the developed scenarios, household organic waste is divided into food waste, human excrement, and food waste and human excrement mixture (**Table 4**). Energy (electric power and diesel) and material (public tap water) are consumed in each transfer and treatment processes, GHG is emitted accordingly, and costs are required. Scenario 6 also evaluated the reduction level of GHG by recovering biogas. If food waste is put out after it has been dried in a FWDM, energy, which is necessary for the use of elevators in apartments, for the collection and transport, and for the transport of the waste to aerobic compositing facilities, will be reduced. If food waste is sent to the public WWTPs after sewage pretreatment in houses, energy for public WWTPs operation will be significantly reduced.

2.4. Key Factors Analysis

2.4.1. Possibility of a Combined Treatment of Household Organic Waste

This study evaluated the characteristics of anaerobic digestion and biogas generation on mixed liquids of grinded food waste and human excrement mixture by the biochemical methane production (BMP) test.

The characteristics of the used samples are shown in **Table 5** and the reaction formula to generate methane, which was calculated based on the measured data, was Equation (1).

$$C_{4.23}H_{6.84}O_{0.58} + 2.23H_2O \rightarrow 1.41CO_2 + 2.83CH_4 \quad (1)$$

The ingredient content in gas, which was calculated based on this formula, was 66.7% of CH_4 and 33.3% of CO_2. The early ingredient content of gas in headspace, which was corrected by considering the solubility of gas ingredients, was 84% of CH_4 and 16% of CO_2. The amount of accumulated methane generation was largest when grinded food waste was 94 mL, and non-thickened human excrement with flush water was 51 mL. The amount of methane generation based on inflow of COD_{Cr} for grinded food waste and for non-thickened human excrement with flush water was 0.342 L CH_4/g COD and 0.423 L CH_4/g COD, respectively.

The existing study showed the range of 0.333 to 0.347 L/g COD_{Cr} [22] on the methane gas generation of mixed samples. Methane gas generation, which was collected after the mixed samples were digested for 20 days, was 0.35 L/g COD_{Cr} per person, thus, the amount of methane gas generation was 24.85 L/person/day for 71 g/day (food waste 35 g + human excrement 36 g) [23].

Table 2. Properties of septic tank sludge and raw human excrement.

Location		Type	BOD (mg/L)	COD (mg/L)	TS (mg/L)	VS* (%)	TN (mg/L)	TP (mg/L)
Korea	Jungnang	Septic tank sludge	11343	9812	19761	85.9	1510	175
		Raw human excrement	13638	12044	34178	76.4	2655	298
	Seonam	Septic tank sludge	7209	3236	6558	-	-	-
		Raw human excrement	-	-	-	-	-	-
	Nanji	Septic tank sludge	8674	-	8000	-	-	-
		Raw human excrement	16059	-	19000	-	-	-
US		Septic tank sludge	6480	-	12862	70.2	588	210
		Raw human excrement	-	-	-	-	-	-

*Based on TS.

Table 3. Characteristics of the developed scenarios.

Scenarios	Food waste disposal units	Food waste collection	Food waste treatment	Human excrement treatment
Scenario 1	-	Curbside	Composting	Septic tank in houses
Scenario 2	-	AVWC system	Composting	Septic tank in houses
Scenario 3	FWDMs in individual houses	Curbside	Compositing	Septic tank in houses
Scenario 4	FWDs in individual houses	Discharge the grinded food waste to the public WWTPs		Septic tank in houses
Scenario 5	FWDs in individual houses	Pretreatment in apartments and discharge the sewage to the public WWTPs		Septic tank in houses
Scenario 6	FWDs in individual houses	Combined biogasification of food waste and human excrement in apartments and discharge the sewage to the public WWTPs		

Table 4. Energy and material consumption, GHG emissions, and recovery in various scenarios.

Organic waste	Process	Users	GHG source	S1	S2	S3	S4	S5	S6
Food waste	Transfer	Elevators	Electric power	○	○	×			
		Collection · transport	Diesel	○		△			
		AVWC systems	Electric power		○				
		Transport to aerobic compositing facilities	Diesel	○	○	△			
	Treatment	FWDMs	Electric power			○			
		FWDs	Electric power				○	○	○
			Tap water				○	○	○
		Sewage pretreatment in apartments	Electric power					○	
		Aerobic compositing facilities	Electric power	○	○	○			
		WWTPs	Electric power				○	△	
Human excrement		Septic tank in apartments	Methane gas	◎	◎	◎	◎	◎	×
Food waste and human excrement mixture		Biogas facilities	Electric power						○
			Biogas						●
		WWTPs	Electric power						△

○: Consumption in full operation, ◎: Emissions in full operation, △: Consumption in half or less operation, ×: Insignificant consumption/emissions, and ●: Recovery in full operation. *S1, S2, S3, S4, S5, and S6 stand for scenarios 1 - 6, respectively.

Meanwhile, the amount of CH_4 generation per person in a septic tank was calculated as 0.423 L CH_4/g COD_{Cr} × 1/2.4 (g COD_{Cr}/g TS) [24] × 27 (TS, cases of toilets in US) [25] × 70% (storage solid material) [24] × 0.12 (room temperature)/0.27 (temperature range of 37˚C - 41˚C) [26] = 1.481 L CH_4/person/day; the weight was 1.481 L × 16 g/22.4 L = 1.058 g/person/day.

2.4.2. Parameters in Process Units

Parameters were calculated by dividing them largely into transfer and treatment processes in **Table 6**, **Table 7**, and **Table 8**. The parameters were calculated as consumption, emission, and recovery by GHC source (electric

Table 5. BMP test of food waste and human excrement.

Item (unit)	pH	COD_{Cr} (mg/L)	COD_{Mn} (mg/L)	TN (mg/L)	NH_3-N (mg/L)	TP (mg/L)
Food waste	4.46	136,887	26,000	6179	2748	2043
Human excrement with flush water	7.79	2388	645.8	111.5	95.3	19.38
Thickened human excrement	7.81	8150	2625.5	770.2	631.5	132.4
Item (unit)	**TS (mg/L)**	**VS (mg/L)**	**VS/TS (%)**	**TSS (mg/L)**	**VSS (mg/L)**	**VSS/TSS (%)**
Food waste	94,303	90,373	95.83	50,601	46,358	91.60
Human excrement with flush water	1800	800	44.44	1130	944.4	83.56
Thickened human excrement	20,649	12,200	59.08	6893	5597	81.20

Table 6. Parameters for transfer processes.

	Parameter estimation
Transfer	**Electric power of the elevator** • Conditions of the elevator: 20 story apartment, 40 households, height between floors: 2.8 m, the speed of the elevator 90 m/min, the rated electric power of the elevator 8.3 kW [27]. • Frequency to put out food waste per household for collection: 10 times per month (20 times for round trip). • The amount to put out food waste per month: 0.63 ton(= 0.0045 ton/household/month × 3.5 p/household × 40 households). • Running distance per month of the elevator: 22400 m (= 40 households × 20 times × 2.8 m × 20 floors ÷ 2). • Used electricity power per month of the elevator: 34.4 kWh(= 8.3 kW × 22400 m ÷ 90 m/min ÷ 60min/hr). • Used electricity energy per ton of food waste: 54.6 kWh(= 34. 4 kWh ÷ 0.63 ton). • Electric charges per ton of food waste: 3 USD (= 34.4 kWh × 0.0551 USD/kWh ÷ 0.63 ton). • Electric power for elevator is excluded when FWDMs are used. **Diesel for collection and transport** • Vehicle conditions: load capacity: 5 tons, transportation distance per day: 37 km, the frequency of collection per day: 3 times, collection amount per day: 15 tons-food waste, fuel efficiency: 3.2 km/L-Diesel. • Consumption of diesel for collection and transport per ton of food waste: 0.8 L/ton(= 37 km ÷ 3.2 km/L ÷ 15 ton). • Cost for collection and transport per ton of food waste: 55.6 USD/ton [28]. • The consumption and the cost of diesel for dried food waste were estimated as 18% of total food waste for FWDMs [29]. **Electric power of an AVWC system** • Conditions of the facilities: The construction cost: 17 million USD, the repair and maintenance cost: 6.8 million USD, the persisting period: 20 years, the amount of waste from an AVWC system for 20 years: 41449 tons. • Used electricity energy per ton of food waste: 324.3 kWh(= 200 kW/hr × 3360 hr ÷ 2072.5 tons). • Construction cost per ton of food waste: 574 USD (= 23.8 million USD ÷ 41449 ton/20 yrs). • Operating cost per ton of food waste: 186 USD/ton [30]. **Diesel for transport of the compositing facilities** • Vehicle conditions: load capacity: 5 tons, total transportation distance: 80 km, frequency of transport: 2 times, transportation amount: 10 tons, fuel efficiency: 4.8 km/L-Diesel, one driver per vehicle. • Consumption of diesel per day of a vehicle: 3.3 L (= 160 km ÷ 4.8 km/L ÷ 10 ton). • Energy consumption per ton of food waste: 34.7 kWh (= 3.3 L × 9050 kcal/L ÷ 860 kWh/kcal). • Transport cost per ton of food waste: 30 USD [31]. The consumption and the cost of diesel for dried food waste were estimated as 18% of total food wastefor FWDMs [29].

Table 7. Parameters for treatment processes.

	Parameter estimation
Treatment	**Electric power of the FWDM [29]** • Energy consumption of the FWDM per ton of food waste: 3481 kWh (= 55 kWh/household/month ÷ 0.0158 ton/month/household). • Cost to purchase the FWDM per ton of food waste: 154 USD/ton (= 295 USD/10 years ÷ 1.92 ton/10 years). • The electric charges of the FWDM per ton of food waste: 192 USD/ton (= 3481 kWh × 0.0551 USD/kWh). **Electric power of the FWD [29]** • Energy consumption of the FWD per ton of food waste: 95 kWh (= 1.5 kWh/household/month ÷ 0.0158 ton/household/month). • Cost to purchase the FWD per ton of food waste: 380 USD (= 730 USD/10 years ÷ 1.92 ton/10 years). • The electric charges of the FWD per ton of food waste: 5.2 USD (= 95 kWh × 0.0551 USD/kWh). **Water use of the FWD [13]** • Water consumption of the FWD per ton of food waste: 27 m^3 (= 0.12 m^3/month/p × 3.5 p/household ÷ 0.0158 ton/household /month). • Rate of water for the FWD per ton of food waste: 8.6 USD (= 27 m^3 × 0.32 USD/m^3). **Electric power of pretreatment facilities [29]** • Conditions of the facilities: For the quality standards of discharge water, BOD is less than 100 mg/L, SS is less than 300 mg/L, n-Hexane is less than 300 mg/L. The treatment capacity is 400 households and the quantity of discharge water per day is 49 m^3. The construction cost is 206 thousand USD (erection of frameworks is 86 thousand USD, the equipment work is 120 thousand USD, this is just used for treatment of food waste by using the combined treatment plant of food waste and human excrement). The persisting period is 10 years and the annual quantity to treat food waste is 0.192 tons. • Energy consumption of the pretreatment: 688 kWh(= 4350 kWh/month ÷ 400 household ÷ 0.0158 ton/household /month). • Construction cost per ton of food waste: 268 USD (= 206 thousand USD ÷ 400 household ÷ 1.92 ton/household/10 years). • Electricity cost per ton of food waste: 38 USD (= 688 kWh × 0.0551 USD/kWh). • Maintenance cost per ton of food waste: 47 USD (= 300 USD/month ÷ 400 household ÷ 0.0158 ton/household/month). **Electric power of the aerobic compositing facilities** • Electric energy consumption per ton of food waste: 111.7 kWh [29]. • Treatment cost per ton of food waste: 80 USD [18]. **Electric power of the public WWTP [29]** • Energy consumption per ton of food waste (sludge treatment, supply of air): 10.3 kWh. • Cost per ton of food waste (sludge treatment, supply of air): 15 USD. • 1 kWh/ton-food waste was applied in treatment (supply of air only in the inflow part) of the pretreatment facilities. • 1.5 USD/ton-food waste was applied in treatment (supply of air only in the inflow part) of the pretreatment facilities. • 1.5 USD/ton-food waste was applied in treatment (supply of air only in the inflow part, the inflow part of human excrement was ignored) of the biogas facilities. **Generation of methane gas in a septic tank** • The conditions of calculation: The amount of human excrement per person per day: 100 g, The amount of human excrement per population (6667 persons, equivalent of 1 ton of food waste generation): 0.6667 ton (= 0.7 ton). • Generation of methane gas per population (6667 persons): 7.054 kg (= 1.058 g/person/day × 6667 person/ton-food waste ÷ 1000 g/ton). • The emissions of methane gas to the air was ignored by forcibly collecting methane gas when 1 ton of food waste and 0.7 ton of human excrement (= mixture 1.7 tons) were combined and treated.

Continued

Treatment	**Electric power of the biogasification facilities (Food waste and human excrement mixture)** • Conditions of the facilities: For the quality standards of discharge water, BOD is less than 100 mg/L, SS is less than 300 mg/L, n-Hexane is less than 300 mg/L. The treatment capacity is 400 households and the quantity of discharge water per day is 49 m^3. The construction cost is 206 thousand USD (erection of frameworks is 86 thousand USD, the equipment work is 120 thousand USD, this is just used for treatment of food waste by using the combined treatment plant of food waste and human excrement). The persisting period is 10 years and the annual quantity to treat food waste is 0.192 tons. • Energy consumption of the biogasification per 1.7 tons of food waste and human excrement mixture: 1147 kWh (= 688 kWh × 1.6667 ton-mixed waste). • Biogas to electric power per 1.7 tons of food waste and human excrement mixture: 502 kWh (= 168 Nm^3 × 9.953 kWh/Nm^3 × 0.3%). • Construction cost per 1.7 tons of food waste and human excrement mixture: 447 USD (= 268 USD × 1.6667 ton-mixed waste). • Electricity cost per 1.7 tons of food waste and human excrement mixture: 63 USD (= 38 USD × 1.6667 ton-mixed waste). • Maintenance per 1.7 tons of food waste and human excrement mixture: 79 USD (= 47.4 USD × 1.6667 ton-mixed waste). • Saving cost by biogas to electric power on site: 28 USD (= 502 kWh × 0.0551 USD/kWh). **GHG avoided effect(LNG saving effect) due to utilization of biogas** • Conditions of calculation: 50.8 kg of CO_2 equiv. is generated when LNG, which is applicable to the caloric value, 1 MJ is produced. • Collection calorie per 1.7 tons of mixture: 6.02 MJ (= 168 Nm^3 × 8560 kcal/Nm^3 methane × 4.1865 × 10^{-6} MJ).

Table 8. Parameters for the social costs and conversion factors.

	Parameter estimation
Social cost	**The value of domestic labor to handle food waste: 10 USD/month [16]** • Conditions of calculation: Time it takes to put out food waste using elevators in apartments: 7.8 min/frequency, time it takes to put out food waste using FWDMs and elevators: 4 min/frequency, time it takes to discharge grinded food waste to the public sewage system using FWDs: 2 min/frequency. • The labor value per ton of food waste when it is generally handled: 633 USD (= 10 USD/month ÷ 0.0158 ton/household/month). • The labor value per ton of food waste when it is handled after using FWDMs: 325 USD (= 633 USD/ton ÷ 7.8 min/frequency × 4 min/frequency). • The labor value per ton of food waste when it is handled after using FWDs: 162 USD (= 633 USD/ton ÷ 7.8 min/frequency × 2 min/frequency). **The value of domestic labor to handle food waste: 34 USD/month [13]** • The labor value per ton of food waste when it is generally handled: 2145 USD (= 33.895 USD/month ÷ 0.0158 ton/household/month). • The labor value per ton of food waste when it is handled after using FWDMs: 1100 USD (= 2145/ton ÷ 7.8 min/frequency × 4 min/frequency). • The labor value per ton of food waste when it is handled after using FWDs: 550 USD (= 2145/ton ÷ 7.8 min/frequency × 2 min/frequency).
	Index to calculate GHG: Diesel 1 L = 7.07 × 10^{-4} ton CO_2 equiv., 1 kWh = 4.24 × 10^{-4} ton CO_2 equiv.

power, diesel, tap water, methane gas) for functional unit: per 1 ton of food waste; per 0.7 ton of human excrement; or per 1.7 tons of mixture.

3. Results and Discussion

3.1. The Environmental Analysis

Figure 2 shows GHG emissions and net energy consumption from 1 ton of household organic waste according to various scenarios. In Scenario 4 (125 kg CO_2 equiv./ton-household organic waste), the grinded food waste discharge to the public WWTP (Human excrement was sent to the existing septic tank) was the best practice. There were increasing emission of GHG in the following order: Scenario 1 (Compositing, 133), Scenario 2 (AVWC system + Compositing, 215), Scenario 5 (FWDs + Pretreatment + Public WWTP, 298), Scenario 6 (FWDs + Biogasification + Public WWTP, 351), and Scenario 3 (FWDM + Compositing, 886).

The evaluation of net energy consumption identified that energy consumption of Scenario 4 was the smallest at 36 kWh/ton-waste. The order of energy consumption was as follows: Scenario 1 (125), Scenario 2 (320), Scenario 6 (445), Scenario 5 (470), and Scenario 3 (2105).

In Scenario 6, GHG emissions were 351 kg CO_2 equiv./ton-household organic waste in the transfer and treatment processes. However, 167 kg of CO_2 equiv.ton-household organic waste was actually generated if the fact that the avoided impact (or saved effect, the LNG alternative effect) of methane gas recovery of 184 kg of CO_2 equiv./ton-household organic waste was considered.

3.2. The Economic Analysis

Figure 3 shows the cost analysis. Scenario 1 (101 USD/ton-household organic waste) was the best, followed by Scenario 3 (221), Scenario 4 (245), Scenario 5 (450), Scenario 2 (558), and Scenario 6 (592). If the cost of 17 USD/ton-waste by using biogas in the private power station was applied, the net cost was 575 USD/ton-waste.

However, the result, which analyzed the social cost by reflecting the value of domestic labor about handling and separating food waste for collection of 10 USD/month, has found that the cost of Scenario 4 (343 USD/ton-household organic waste) was most efficient followed by Scenario 3 (416), Scenario 1 (481), Scenario 5 (547), Scenario 6 (689; net cost 672), Scenario 2 (938), in order.

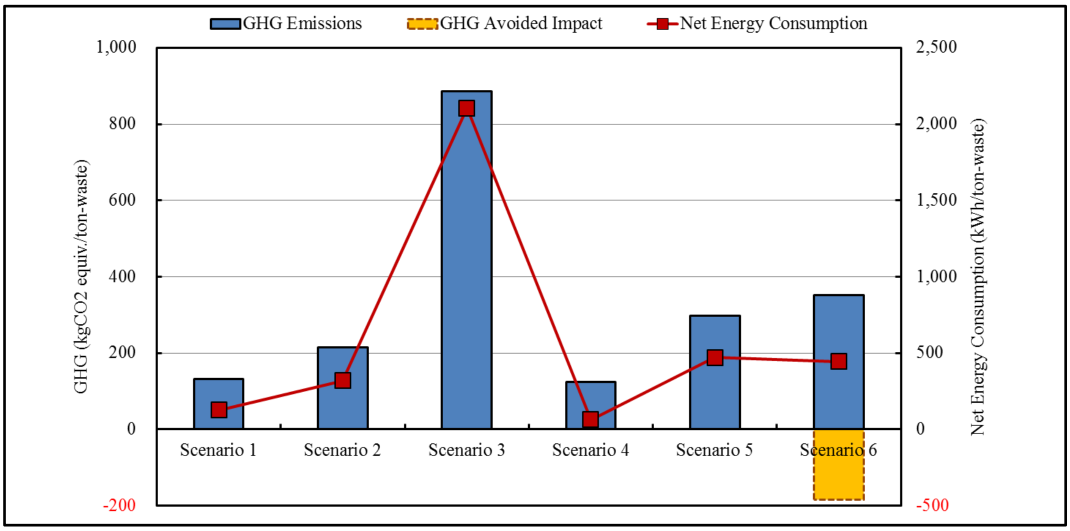

Figure 2. GHG emissions and net energy consumption in various scenarios.

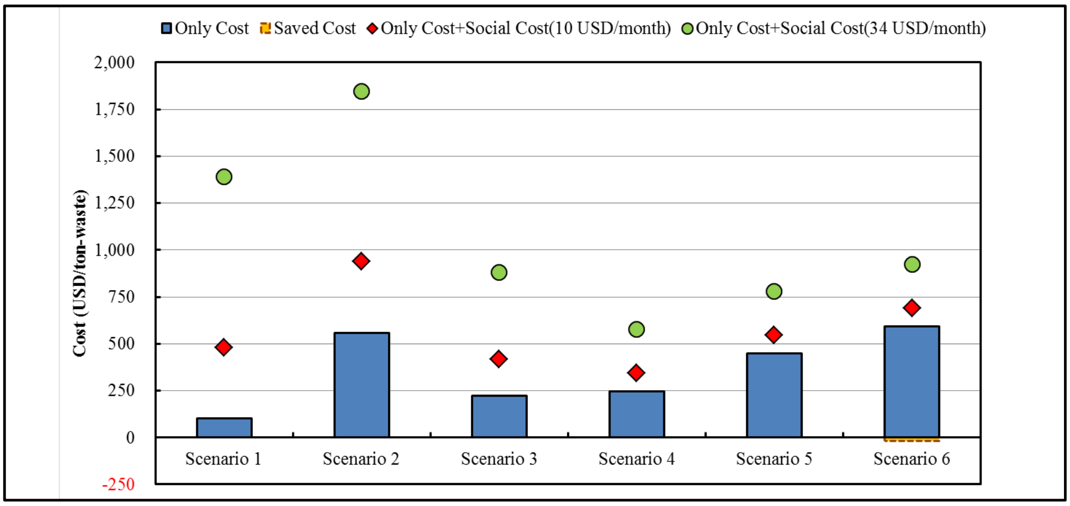

Figure 3. Cost analysis in various scenarios.

By considering domestic labor of 34 USD/month, the cost of Scenario 4 (575 USD/ton-household organic waste) was the most efficient followed by Scenario 5 (779), Scenario 3 (881), Scenario 6 (922; net cost 905), Scenario 1 (1388), and Scenario 2 (1845) in order.

4. Conclusions

In the environmental aspect, the scenarios including only compositing and only FWDs have been proved to be superior. The utilization of biogas in the private power station after the FWDs and domestic sewage pretreatment in the apartments was better in the GHG emissions and energy consumption than the discharge to the public WWTP after the FWDs and domestic sewage pretreatment in the apartments.

The scenario including only composting was superior to the other scenarios in the economic aspect. In considering the only transfer and treatment processes, the study discovered that the method to put out food waste by using elevators was less expensive, yet, it incurred higher social cost on handling and separating food wastes; thus, it was more efficient to use FWDs. Furthermore, the energy saving effect due to recovery of biogas has found to be larger in the environment aspect than in the economic aspect.

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