Life Cycle Assessment of BioHiTech Digester for Food Waste Management

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August 1, 2018

Executive Summary

In 2015, the University of Delaware installed two BioHiTech digesters in their new, state-of-the-art dining common. Building on this initiative, the goal of this project was to evaluate the environmental impact of BioHiTech's digester system for diverting food waste from a landfill and then releasing the effluent into the sewer for further processing in a wastewater treatment plant (WWTP) relative to other food waste management strategies.

A life cycle assessment (LCA) was conducted in accordance with the ISO 14040 standards to enable a gate-to-grave comparative assessment of four possible food waste management pathways, including (1) transporting aerobically digested food waste through the sewer to a wastewater treatment plant for further treatment (Aerobic-WWTP), (2) trucking aerobically digested food waste to an anaerobic digester for further treatment and conversion into energy (Aerobic-AD), (3) trucking food waste to a landfill for disposal (T-L), and (4) trucking food waste to a compost facility for further treatment (T-C).

In conducting the LCA, the relative environmental impact of all four pathways was determined by comparing several key impact categories. First, and foremost, the global warming potential (GWP) of each pathway was computed. This is widely considered the most important environmental indicator. Three additional impact categories, acidification potential (AP), eutrophication potential (EP), and photochemical/smog particulate formation potential (PSFP), were also assessed.

The LCA results show that the disposal of food waste using BioHiTech's aerobic digestion system followed by release of the effluent to the sewer is an environmentally favorable pathway. In terms of global warming potential, Aerobic-WWTP is far better than transporting food waste directly to the landfill, the pathway that has, far and away, the most negative environmental impact. Furthermore, in terms of global warming potential, Aerobic-WWTP compares well to both transferring food waste to a compost facility and to the pathway that includes aerobic digestion followed by trucking the aerobically digested food waste to an anaerobic digester for further treatment and conversion into energy. Finally, Aerobic-WWTP also compares well to all of the other pathways in terms of the three additional environmental impact factors. Future work will be conducted to assess the relative positive and negative impacts of the aerobic digester effluent on the wastewater system in general, and WWTPs in particular.

Project Goal

In 2015, the University of Delaware installed two BioHiTech digesters in their new, state-of-the-art Caesar Rodney dining common. The next logical phase of this initiative was to understand and quantify the environmental aspects and potential benefits of the BioHiTech digester system for diverting food waste from a landfill to a wastewater treatment plant. This study aimed to facilitate an in-depth understanding of BioHiTech digester technology in order to help stakeholders (e.g., customers, regulators, and municipalities) better assess the role of the BioHiTech digester system in their food waste management program.

Project Scope

To achieve the project goal, a life cycle assessment (LCA) was conducted in accordance with the ISO 14040 standards to enable a gate-to-grave comparative assessment of four potential food waste management pathways. The four pathways investigated (shown in Figure 1) are (1) transporting aerobically digested food waste through the sewer to a wastewater treatment plant for further processing (Aerobic-WWTP), (2) trucking aerobically digested food waste to an anaerobic digester for further treatment and conversion into energy (Aerobic-AD), (3) trucking food waste to a landfill for disposal (T-L), and (4) trucking food waste to a compost facility for further treatment (T-C). The system boundaries for the LCA are shown in Figure 1 and include all activities from waste disposal through treatment and final disposal.

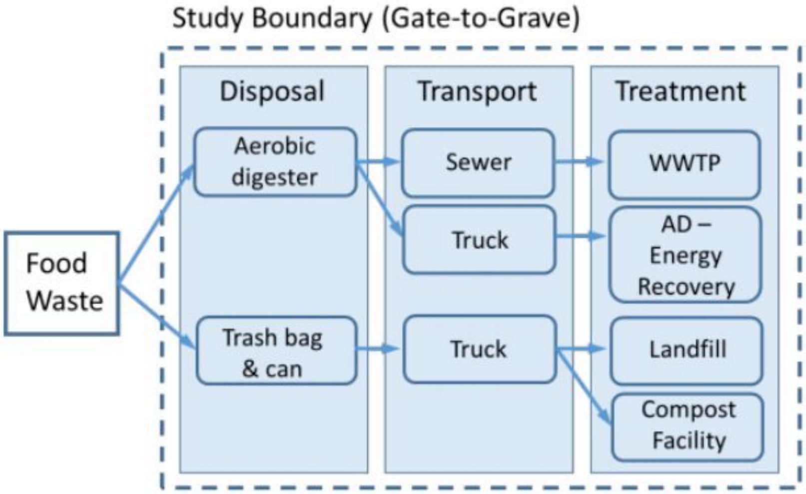


Figure 1: Simplified process flows and boundaries for food waste disposal pathways

Environmental Impact Parameters

Four environmental impact parameters were selected for consideration. The most significant impact parameter assessed was overall global warming potential (GWP). Also evaluated were acidification potential (AP), eutrophication potential (EU), and photochemical smog formation potential (PSFP). Definitions of each of the four impact parameters are shown in Table 1.

Table 1: Definition of environmental impacts

Impact Parameter	Characteristics
Global Warming Potential (GWP)	Global warming potential is a measure of the amount of greenhouse gases that trap heat in the atmosphere, which a process produces.
Acidification Potential (AP)	Acidification potential is a measure of the amount of hydrogen ions, that get deposited in soil or water, which a process produces.
Eutrophication Potential (EP)	Eutrophication potential is a measure of the amount of nutrients (phosphorus and nitrogen), that can get into inland waterways, which a process produces.
Photochemical/ Smog Forming Potential (PSFP)	Photochemical/smog forming potential is a measure of the amount of VOCs (volatile organic compounds) and nitrogen oxides, that react in sunlight, causing the formation of air pollutants, which a process produces.

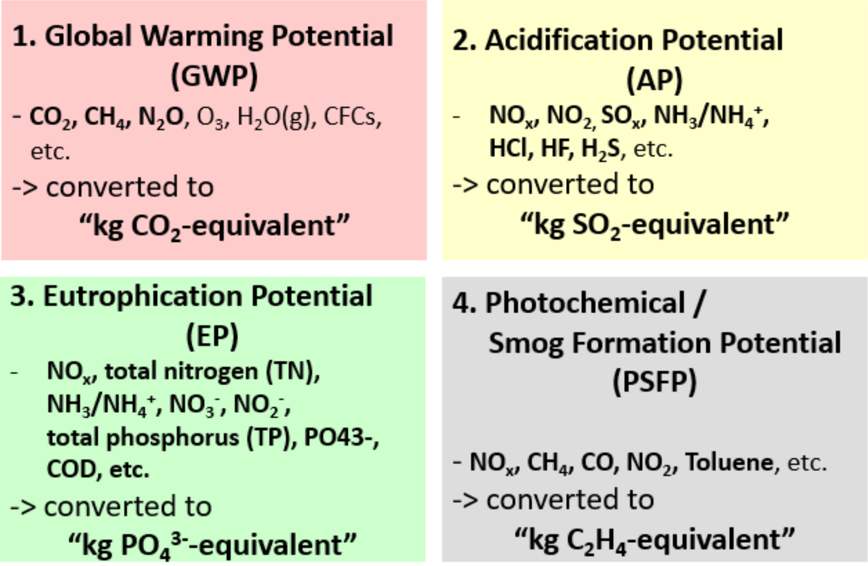
Global warming potential was selected because it is the best single measure of a processes environmental impact. GWP reflects the impact of a process on global warming. **Eutrophication** and **acidification potential** were considered as they capture impacts on water and soil, and **photochemical smog formation** was considered as it captures impacts on air quality.

By quantifying the impact parameters of global warming potential, eutrophication, acidification, and photochemical smog formation, the consequences for both human health (climate change, photochemical and particulate matter formation) and ecosystem quality (acidification and eutrophication) can be assessed. Table 2 provides a list of the consequences of the four impact parameters, while Figure 2 shows the chemical compounds that were considered when computing the magnitude of the global warming, eutrophication, acidification, and photochemical smog formation potentials.

Table 2: Consequences of environmental impacts

Impact Parameter	Characteristics
Global Warming Potential (GWP)	• The combined radiation effects of gases trapped in our atmosphere resulting in higher temperatures and more sudden climatic variability. • GWP can be associated with burning of fossil fuels for energy and landfilling (e.g., release of methane, carbon dioxide, nitrous oxide and other contaminants).
Acidification Potential (AP)	• An air pollutant measure linked to leaching of nitrogen, release of sulfur dioxide, and ammonia volatilization that can increase the acidity of water and soils.
Eutrophication Potential (EP)	• Often results from an ecosystem overload of nitrogen and phosphorus caused by runoff from agricultural, industrial, or wastewater sources. • These excess nutrients can create rapid biomass growth and decay in water and soil, causing oxygen depletion in these environments.
Photochemical/	• Smog is formed when VOCs (volatile organic compounds) and nitrogen

Smog Forming Potential (PSFP)	oxides react in sunlight, causing the formation of pollutants detrimental to human health and the environment.



1. Global Warming Potential (GWP)

- **CO_2, CH_4, N_2O**, O_3, $H_2O(g)$, CFCs, etc.

-> converted to **“kg CO_2-equivalent”**

2. Acidification Potential (AP)

- **NO_x, NO_2, SO_x, NH_3/NH_4^+, HCl, HF, H_2S**, etc.

-> converted to **“kg SO_2-equivalent”**

3. Eutrophication Potential (EP)

- **NO_x, total nitrogen (TN), NH_3/NH_4^+, NO_3^-, NO_2^-, total phosphorus (TP), PO43-, COD, etc.**

-> converted to **“kg PO_4^{3-}-equivalent”**

4. Photochemical / Smog Formation Potential (PSFP)

- **NO_x, CH_4, CO, NO_2, Toluene**, etc.

-> converted to **“kg C_2H_4-equivalent”**

Figure 2: Quantifying impact through Life Cycle Impact Analyses

* Bolded chemical compounds indicate the emissions that have been included in our analysis

LCA Analysis

The life cycle assessment analysis consisted of (1) process clarification, (2) life cycle inventory collection, and (3) impact analysis. For process clarification, a series of process maps that disaggregate inflows and outflows of potential releases were developed, which are provided in Appendix A. Figure 3 shows a generalized process map for the Aerobic-WWTP pathway.

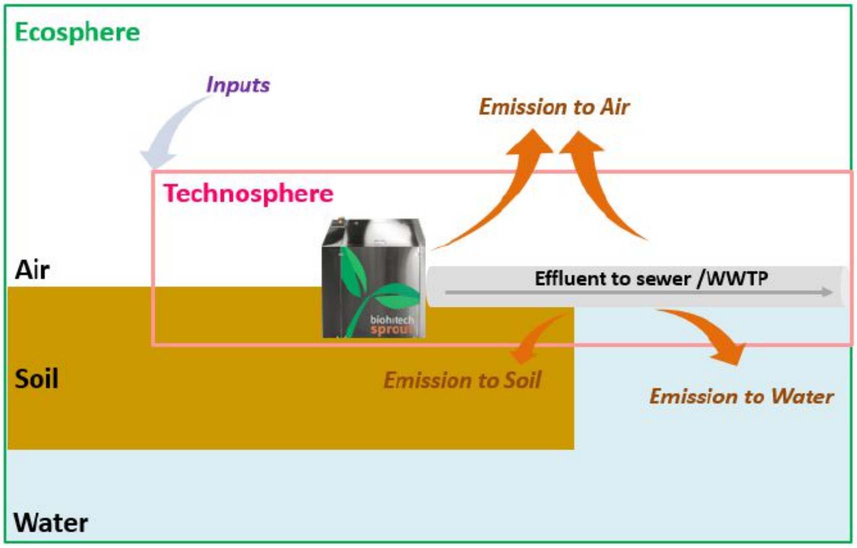


Figure 3: Generalized process diagram of inputs and outputs for the Aerobic-WWTP pathway

For life cycle inventory collection, data related to each of the four treatment pathways was assembled from a variety of literature sources related to typical food waste disposal processes as well as published data from BioHiTech (Aerobic-WWTP, Aerobic-AD, T-L, and T-C). This led to the creation of detailed inventories of individual components with environmental release potential relevant to the disposal, transport, and treatment phases within each of the pathways. These inventories, which are summarized in Appendix B, were then disaggregated further based on their relevance to the four environmental impact categories (GWP, AP, EP, and PSFP). To aid in the comparison, conversion factors were applied to individual components to establish common equivalent units of measurement (CO_2-eq, SO_2-eq, PO_4^{3-}-eq, C_2H_4-eq).

For the impact analysis, a functional unit of 1,000 kg of food waste and a 100-year time horizon for environmental emissions was used. The total impact for each category was defined as the sum of direct emissions + indirect emissions.

LCA Results

Using the data inventories developed, the total emissions computed for the four impact categories for each of the four pathways are given in Table 3.

Table 3: Life cycle impact indicators per functional unit (1000 kg/food waste)

IMPACT CATEGORY	Units	PATHWAY			
		Aerobic Digestion to Wastewater Treatment Plant (Aerobic-WWTP)	**Aerobic Digester to Anaerobic Digestion for energy recovery (Aerobic-AD)**	**Trash including Organics to Landfill Facility (T-L)**	**Organics to Composting Facility (T-C)**
Global Warming Potential (GWP)	kg CO_2 eq	60	100	600	120
Acidification Potential (AP)	kg SO_2 eq	0.028	0.26	0.74	0.35
Eutrophication Potential (EP)	kg PO_4^{3-} eq*	0.0091	0.28	0.76	0.30
Photochemical/ Smog Forming Potential (PSFP)	kg C_2H_4 eq**	0.010	0.070	0.16	0.084

*Reported in PO_4^{3-}-eq instead of N-eq due to relevant conversions (accepted practice)

** Reported in C_2H_4-eq instead of O_3-eq due to relevant conversions (accepted practice)

It should be noted that offsets can significantly reduce the total emissions (in some cases they can even lead to negative LCA values). These offsets can be derived from, among other things, energy recovery, carbon sequestration, and recovery of important soil nutrients, such as nitrogen and phosphorus that can be used to make fertilizers. Each disposal pathway has opportunities for offsets, but the degree to which they are taken advantage of in any particular situation differs greatly (for example, one landfill may recover methane and another may not). Furthermore, the efficiency of the production of the "products" that result in the offset varies greatly. Finally, negative effects such as odors caused by large composting facilities adds yet another layer of complexity in incorporating these impacts into the LCA. As a result of the large variability and large uncertainty related to potential offsets, they have not been included in the results given in Table 3. Further discussion related to such complexities is given in the Appendices.

Conclusions and Recommendations

Having used the best available data, the LCA results show that the disposal of food waste using BioHiTech's aerobic digestion system followed by release of the effluent to the sewer is an environmentally favorable pathway. In terms of global warming potential, Aerobic-WWTP is far better than transporting food waste directly to the landfill, the pathway that has, far and away, the most negative environmental impact. Furthermore, in terms of global warming potential, Aerobic-WWTP compares well to both transferring food waste to a compost facility and to the pathway that includes aerobic digestion followed trucking the aerobically digested food waste to an anaerobic digester for further treatment and conversion into energy. Finally, Aerobic-WWTP also compares well to all of the other pathways in terms of the three additional environmental impact factors (acidification potential (AP), eutrophication potential (EP), and photochemical/smog particulate formation potential (PSFP)).

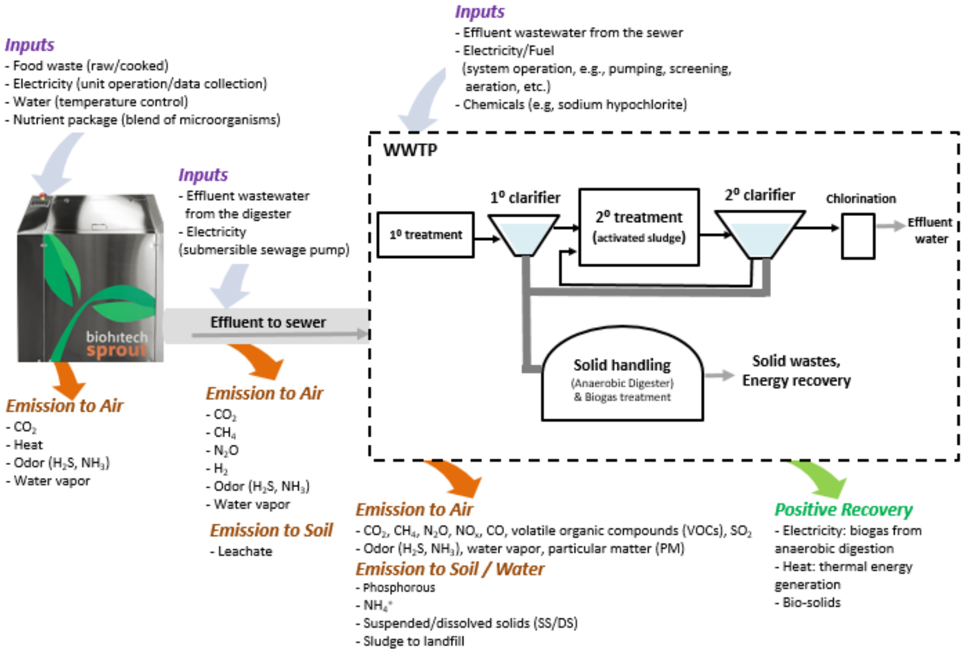
In conducting any LCA, the results are dependent on the quantity, quality, and accuracy of the data that is available. The values given in Table 3 are the best estimates that could be made with the available data. It would be beneficial to put ranges on the values, especially the GWP numbers. To do this would require a larger quantity of data on emissions than is currently available for some of the processes.

In making the conclusions, it is important to note the assumptions and limitations of the analysis. Appendix C describes the assumptions and limitations of this study. Furthermore, there are always factors that have to be evaluated qualitatively because they are difficult or impossible to quantify. Appendix D speaks to considerations that are hard to quantify but should be considered in the final evaluation of environmental impact. Finally, Appendix E contains the references from which the data was sourced.

As described in Appendix D, the release of aerobic digester effluent into the wastewater system raises a number of interesting questions regarding its impact, especially on WWTPs. Future work will be conducted to assess the relative positive and negative effects of the aerobic digester effluent on the wastewater system in general, and WWTPs in particular.

Appendix A: Food Waste Treatment Pathways

Aerobic Digestion to WWTP


Inputs
- Food waste (raw/cooked)
- Electricity (unit operation/data collection)
- Water (temperature control)
- Nutrient package (blend of microorganisms)

Emission to Air
- CO_2
- Heat
- Odor (H_2S, NH_3)
- Water vapor

Inputs
- Effluent wastewater from the digester
- Electricity (submersible sewage pump)

Effluent to sewer

Emission to Air
- CO_2
- CH_4
- N_2O
- H_2
- Odor (H_2S, NH_3)
- Water vapor

Emission to Soil
- Leachate

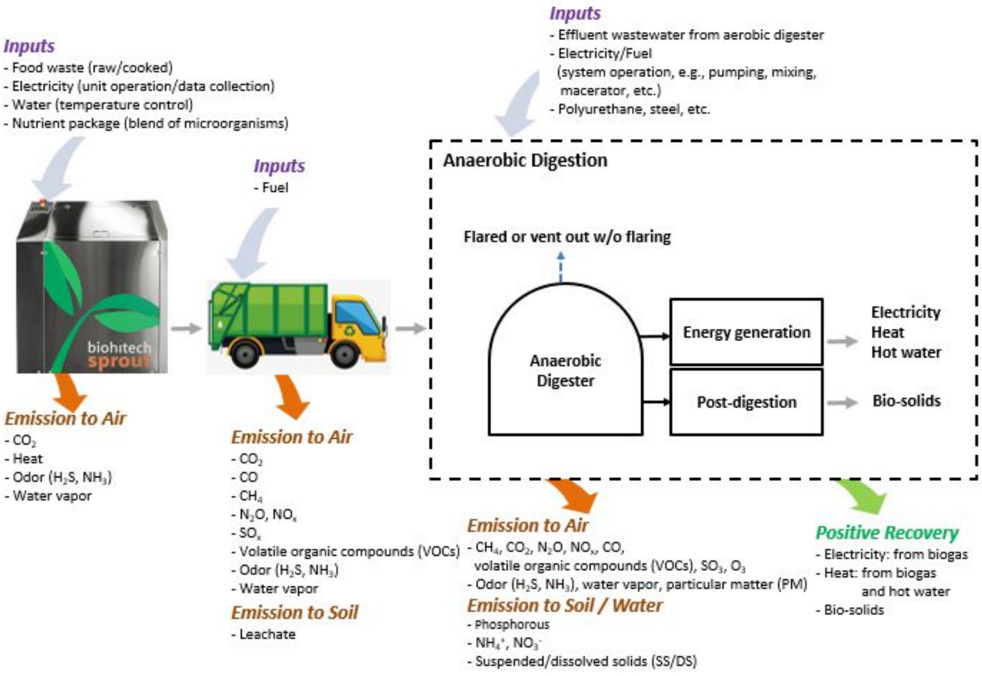
Inputs
- Effluent wastewater from the sewer
- Electricity/Fuel (system operation, e.g., pumping, screening, aeration, etc.)
- Chemicals (e.g, sodium hypochlorite)

Emission to Air
- CO_2, CH_4, N_2O, NO_x, CO, volatile organic compounds (VOCs), SO_2
- Odor (H_2S, NH_3), water vapor, particular matter (PM)

Emission to Soil / Water
- Phosphorous
- NH_4^+
- Suspended/dissolved solids (SS/DS)
- Sludge to landfill

Positive Recovery
- Electricity: biogas from anaerobic digestion
- Heat: thermal energy generation
- Bio-solids

Aerobic Digestion to Anaerobic Digester


Inputs
- Food waste (raw/cooked)
- Electricity (unit operation/data collection)
- Water (temperature control)
- Nutrient package (blend of microorganisms)

Emission to Air
- CO_2
- Heat
- Odor (H_2S, NH_3)
- Water vapor

Inputs
- Fuel

Emission to Air
- CO_2
- CO
- CH_4
- N_2O, NO_x
- SO_x
- Volatile organic compounds (VOCs)
- Odor (H_2S, NH_3)
- Water vapor

Emission to Soil
- Leachate

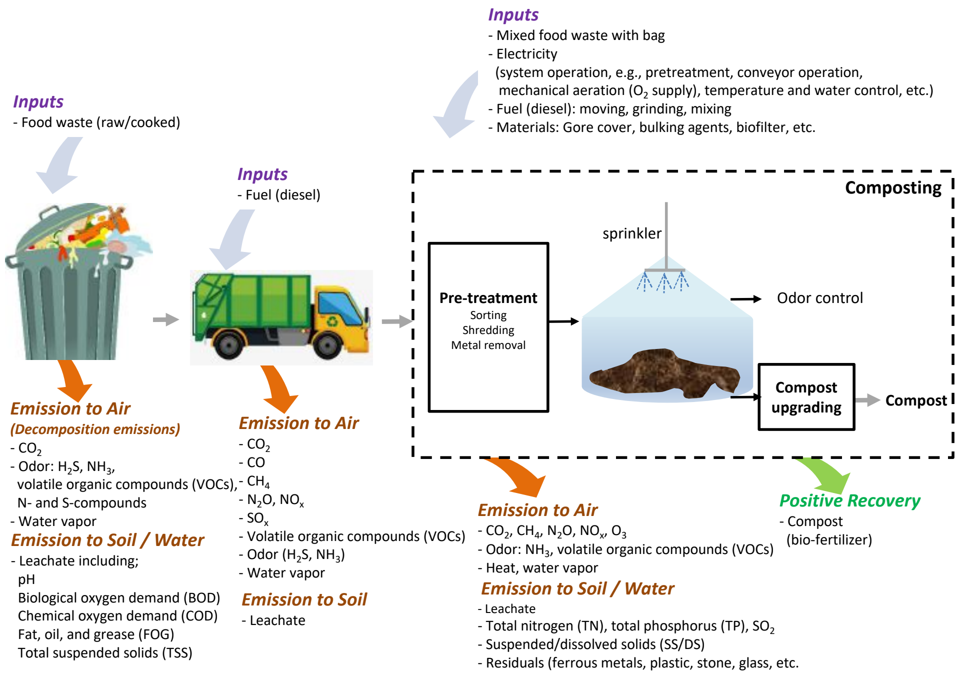
Inputs
- Effluent wastewater from aerobic digester
- Electricity/Fuel (system operation, e.g., pumping, mixing, macerator, etc.)
- Polyurethane, steel, etc.

Emission to Air
- CH_4, CO_2, N_2O, NO_x, CO, volatile organic compounds (VOCs), SO_3, O_3
- Odor (H_2S, NH_3), water vapor, particular matter (PM)

Emission to Soil / Water
- Phosphorous
- NH_4^+, NO_3^-
- Suspended/dissolved solids (SS/DS)

Positive Recovery
- Electricity: from biogas
- Heat: from biogas and hot water
- Bio-solids

Trash Can & Bag to Composting Facility



Inputs
- Food waste (raw/cooked)

Inputs
- Fuel (diesel)

Inputs
- Mixed food waste with bag
- Electricity
 (system operation, e.g., pretreatment, conveyor operation, mechanical aeration (O_2 supply), temperature and water control, etc.)
- Fuel (diesel): moving, grinding, mixing
- Materials: Gore cover, bulking agents, biofilter, etc.

Composting

Pre-treatment
Sorting
Shredding
Metal removal

sprinkler

Odor control

Compost upgrading

Compost

Emission to Air
(Decomposition emissions)
- CO_2
- Odor: H_2S, NH_3, volatile organic compounds (VOCs), N- and S-compounds
- Water vapor

Emission to Soil / Water
- Leachate including;
 pH
 Biological oxygen demand (BOD)
 Chemical oxygen demand (COD)
 Fat, oil, and grease (FOG)
 Total suspended solids (TSS)

Emission to Air
- CO_2
- CO
- CH_4
- N_2O, NO_x
- SO_x
- Volatile organic compounds (VOCs)
- Odor (H_2S, NH_3)
- Water vapor

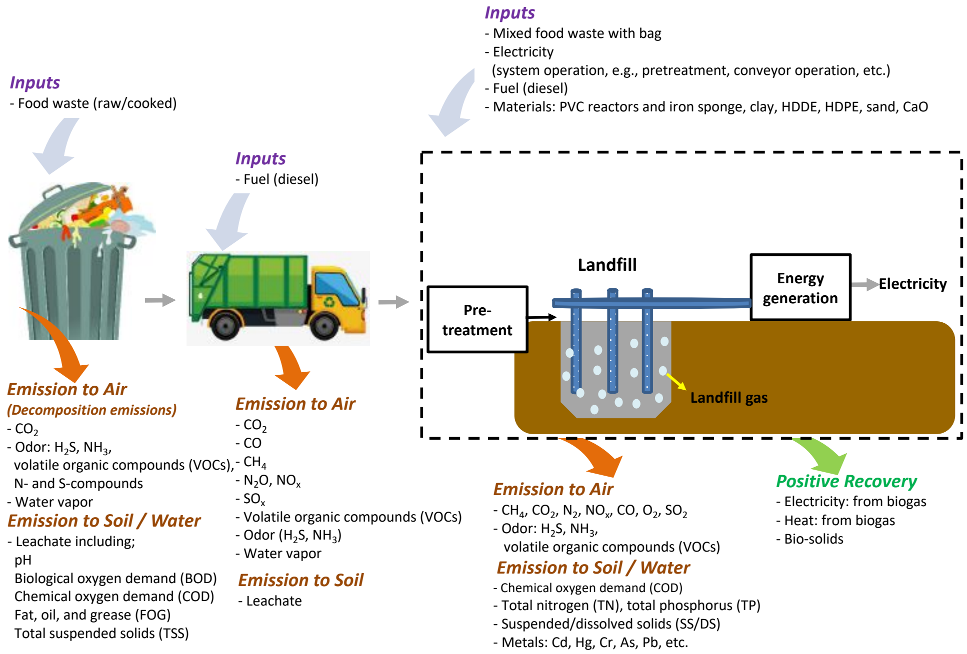
Emission to Soil
- Leachate

Emission to Air
- CO_2, CH_4, N_2O, NO_x, O_3
- Odor: NH_3, volatile organic compounds (VOCs)
- Heat, water vapor

Emission to Soil / Water
- Leachate
- Total nitrogen (TN), total phosphorus (TP), SO_2
- Suspended/dissolved solids (SS/DS)
- Residuals (ferrous metals, plastic, stone, glass, etc.

Positive Recovery
- Compost (bio-fertilizer)

Trash Can & Bag to Landfill



Inputs
- Food waste (raw/cooked)

Inputs
- Fuel (diesel)

Inputs
- Mixed food waste with bag
- Electricity
 (system operation, e.g., pretreatment, conveyor operation, etc.)
- Fuel (diesel)
- Materials: PVC reactors and iron sponge, clay, HDDE, HDPE, sand, CaO

Pre-treatment

Landfill

Energy generation

Electricity

Landfill gas

Emission to Air
(Decomposition emissions)
- CO_2
- Odor: H_2S, NH_3, volatile organic compounds (VOCs), N- and S-compounds
- Water vapor

Emission to Soil / Water
- Leachate including;
 pH
 Biological oxygen demand (BOD)
 Chemical oxygen demand (COD)
 Fat, oil, and grease (FOG)
 Total suspended solids (TSS)

Emission to Air
- CO_2
- CO
- CH_4
- N_2O, NO_x
- SO_x
- Volatile organic compounds (VOCs)
- Odor (H_2S, NH_3)
- Water vapor

Emission to Soil
- Leachate

Emission to Air
- CH_4, CO_2, N_2, NO_x, CO, O_2, SO_2
- Odor: H_2S, NH_3, volatile organic compounds (VOCs)

Emission to Soil / Water
- Chemical oxygen demand (COD)
- Total nitrogen (TN), total phosphorus (TP)
- Suspended/dissolved solids (SS/DS)
- Metals: Cd, Hg, Cr, As, Pb, etc.

Positive Recovery
- Electricity: from biogas
- Heat: from biogas
- Bio-solids

Appendix B: Life Cycle Inventory Summaries for Disposal, Transport, and Treatment

Table B1. LC inventory analysis for DISPOSAL per functional unit (1,000 kg of food waste)[1, 2]

	Disposal					
	Aerobic Digester	**unit**	**Reference**	**Trash Can & Bag**	**unit**	**Reference**
Input						
Energy consumption	20-40	kWh/month	BioHiTech			
Water consumption	75-150	gallons/day	BioHiTech			
Materials						
Nutrient package (as inoculum)	-	-	BioHiTech			
Output						
CO2	42.62	kg	Gangrade and Williamson, 2017			
TP	0	kg	Measurement from UD			
TN	0.35	kg	Measurement from UD			
NH3				5.01E-07	kg	Di et al., 2013
NH4+	8.44E-03	kg	Measurement from UD	4.41E-08	kg	Di et al., 2013
NO3-	0.03	kg	Measurement from UD			
NO2-	0	kg	Measurement from UD			
Toluene				1.60E-06	kg	Di et al., 2013

Assumptions:

[1] Aerobic Digester considered an "in-vessel composting" system (Grngrade and Williamson, 2017; UD Fall 2017 class).

[2] Volume of discharge from Aerobic Digester.

Table B2. LC inventory analysis for TRANSPORT per functional unit (1,000 kg of food waste)[1,2,3]

	Transport					
	Sewer	unit	Reference	Truck	unit	Reference
Input						
Energy consumption *Electricity, submersible sewage (centrifugal) pump operation*	1722	MWh/yr	Kyung et al., 2017			
Diesel				1.53	L	NREL > Transport, combination truck, diesel powered
Output						
CO2				4.50	kg	NREL > Transport, combination truck, diesel powered
CH4	0.03	kg	Liu et al., 2015	7.26E-05	kg	NREL > Transport, combination truck, diesel powered
H2S	6.96E-03	kg	Hvitved-Jacobsen et al., 2005			
N2O				1.12E-04	kg	NREL > Transport, combination truck, diesel powered
NOx				0.03	kg	NREL > Transport, combination truck, diesel powered
CO				7.15E-03	kg	NREL > Transport, combination truck, diesel powered
SO2				0.02	kg	Nabavi-Pelesaraei et al., 2017
NH3				3.06E-04	kg	Nabavi-Pelesaraei et al., 2017
Toluene	0.01	kg	Quigley et al., 1995			
Benzene				0.25	kg	Nabavi-Pelesaraei et al., 2017

Assumptions:

[1] Truck travels 35 miles round-trip for waste pick up (EPA, 2002).

[2] Average heavy truck gets 8 mpg fuel efficiency.

[3] 1 MJ of diesel equivalent to 0.006825 gallons of diesel.

Table B3(a). LC inventory analysis for TREATMENT per functional unit (1,000 kg of food waste)[1,2,3]

	Treatment		
	WWTP	unit	Reference
Input			
Energy consumption	0.30-0.54	kWh	Guerrini et al., 2017; EPA, 2014; Godin et al., 2012
Materials			
Aluminum sulphate (for phosphorus removal)	0.02	kg	Godin et al., 2012
Sodium hydroxide (at primary sedimentation)	8.35E-03	kg	EPA, 2014
Sodium hypochlorite (at disinfection)	1.30E-03	kg	EPA, 2014
Polymer (polyacrylamide for sludge thickening and dewatering)	4.80E-03	kg	EPA, 2014
Output			
CO2	0.24	kg	Campos et al., 2016
CH4	0.63	kg	Godin et al., 2012
N2O	2.20E-05	kg	Godin et al., 2012
NOx	6.19E-06	kg	EPA, 2014
SO2	7.70E-07	kg	EPA, 2014
COD	0.04	kg	Godin et al., 2012
NH4+	7.85E-03	kg	Godin et al., 2012
NO3-	0.01	kg	Godin et al., 2012
TP	3.83E-04	kg	Godin et al., 2012
Energy Recovery			
Electricity recovery from the biogas of AD	0.090-0.096	kWh	Stillwell et al., 2010; EPA, 2007

Assumptions:

[1] General procedure without collection of wastewater influent (1' phy, 2' biology, 3' nutrient treatment (w/ clarifier), and sludge treatment w/ AD) were considered.

[2] Electric energy recovery from AD gas (electricity recovery results in fewer emissions) and partial flaring of AD gas (direct emission to air) were considered.

[3] Biosolids utilization, treatment (sending to landfill or composting) or energy recovery from treatment (many processes utilize partial landfill) are not considered.

Table B3(b). LC inventory analysis for TREATMENT per functional unit (1,000 kg of food waste)[1,2]

	Treatment		
	Anaerobic Digestion	**unit**	**Reference**
Input			
Energy consumption			
Electricity	34-101	kWh	Ardolino et al., 2017; Righi et al., 2013
Heat	338	kWh	Ardolino et al., 2017
Water			
Rain water	46	L	Righi et al., 2013
Fresh water	20	L	Righi et al., 2013
Materials			
Polyurethane (for AD system insulation)	2.5	kg/m3 (volume of AD)	Mezzullo et al., 2012
Polyelectrolyte (as flocculants)	0.15	kg	Righi et al., 2013
Lubricating oil (as flocculants)	0.1	kg	Righi et al., 2013
Output			
CO2	36.54	kg	Gao et al., 2017
CH4	0.74	kg	Tong et al., 2018
N2O	2.76E-03	kg	Tong et al., 2018
NOx	0.25	kg	Tong et al., 2018
SO2	0.23	kg	Gao et al., 2017
H2S	5.05E-05	kg	Gao et al., 2017
NH4+	5.00E-03	kg	Ardolino et al., 2017
COD	0.13	kg	Ardolino et al., 2017
HCl	6.00E-03	kg	Righi et al., 2013
CO	0.4	kg	Righi et al., 2013
Energy Recovery			
Electricity	175	kWh	Righi et al., 2013

Assumptions:

[1] General procedure without collection of wastewater influent (1' phy, 2' biology, 3' nutrient treatment (with clarifier), and sludge treatment with AD) were considered.

[2] No biosolids utilization, treatment (sending them to landfill or composting) or energy recovery from that treatment (many of them are done as a part of landfill) are not considered.

Table B3(c). LC inventory analysis for TREATMENT per functional unit (1,000 kg of food waste)

	Treatment		
	Landfill	unit	Reference
Input			
Energy consumption			
Electricity	2.80	kWh	Righi et al., 2013
Diesel	0.65	L	Righi et al., 2013
Materials			
Sand (for layering)	1.30	m3	Xu et al., 2015
Pesticides (for sanitary)	0.12	m3	Xu et al., 2015
CaO (reduction of leachate color and turbidity)	577	kg	Xu et al., 2015
Output			
CO_2	221.35	kg	Gao et al., 2017
CH_4	14.70	kg	Gao et al., 2017
N_2O	4.55E-05	kg	Kim and Kim, 2010
NO_x	4.00E-02	kg	Righi et al., 2013
SO_2	0.14	kg	Gao et al., 2017
H_2S	9.84E-04	kg	Gao et al., 2017
TP	4.76E-04	kg	Xu et al., 2015
PO_4^{3-}	0.27	kg	Gao et al., 2017
TN	4.63E-02	kg	Xu et al., 2015
NH_3	3.50E-02	kg	Xu et al., 2015
NH_4^+	0.57	kg	Lee et al., 2017
COD	1.10	kg	Lee et al., 2017
HCl	1.06E-02	kg	Lee et al., 2017
HF	2.12E-03	kg	Lee et al., 2017
CO	0.68	kg	Gao et al., 2017
Toluene	1.68E-08	kg	Ying et al., 2012
Energy Recovery			
Electricity	32.00	kWh	Righi et al., 2013

Table B3(d). LC inventory analysis for TREATMENT per functional unit (1,000 kg of food waste)

	Treatment		
	Composting	unit	Reference
Input			
Energy consumption			
Electricity	62-117	kWh	Lee et al., 2017; Righi et al., 2013; Kim and Kim, 2010
Diesel	0.64	L	Righi et al., 2013
Water			
Rain water	85	L	Righi et al., 2013
Fresh water	35	L	Righi et al., 2013
Materials			
Saw dust (for moisture control, reduce toxicity from FW, and remove odor)	170	kg	Lee et al., 2017; Kim and Kim, 2010
Output			
CO2	42.64	kg	Gao et al., 2017
CH4	3.06	kg	Gao et al., 2017
N2O	7.74E-05	kg	ExioBase
NOx	0.31	kg	Gao et al., 2017
SO2	8.70E-02	kg	Gao et al., 2017
H2S	0.02	kg	Righi et al., 2013
PO43-	1.40E-02	kg	Gao et al., 2017
NH3	4.13E-05	kg	Komilis et al., 2006
COD	4.75E-02	kg	Gao et al., 2017
CO	0.10	kg	Gao et al., 2017
Positive Recovery			
Compost product	0.21-0.23	ton	Tong et al., 2018; Righi et al., 2013

Appendix C: Assumptions and Limitations

Data collection is the most laborious, yet critically important, component of any Life Cycle Assessment. In conducting an LCA, there are always limitations in the available data. In this case, unfortunately, a comprehensive bank of information on the outputs of food waste processing and treatment does not exist. This is partially the case because food waste is highly heterogeneous depending on countless variables from geographic location to culture. In addition to the variability of the input material, the processes involved in the disposal, transport, and further treatment of the waste are also highly variable. International databases and published literature were sourced to gather a sense of the food waste influences across the four process pathways, providing the best possible indication of impact.

As a result of the limitations in the data available, assumptions must be made when finalizing the data ultimately used in the LCA. In this case, a series of important assumptions and limitations were made for each of the four food waste management pathways to acknowledge the data variability:

1. It was difficult to find commonly accepted/published detailed nationwide or worldwide data for this life cycle inventory. However, the team was able to gather general data that was applied, as best as possible, to our functional unit (1,000 kg of food waste) across the four different pathways. When data related specifically to food waste was not available, organic solid waste values were applied.
2. Emissions data for individual steps within the WWTP were only partially available. Therefore, emissions data from the overall WWTP operation and from the effluent of the WWTP were used.
3. Most available data were based on human or mixed wastewater, rather than influent composed of purely food waste. Therefore, 183.75 gallons of effluent wastewater from an aerobic digester was used for computing the life cycle inventory (e.g., approximately 100 gallons of wastewater effluent produced by every 1,200 lbs of food digested in an in-vessel aerobic digester).

Additional assumptions specific to the disposal, transport, and treatment of the food waste (1,000 kg) are provided in Appendix B.

Even considering the assumptions made around data variability, the results provide a strong measure of the environmental impact of BioHiTech's digesters relative to the other food waste management processes considered.

It is important to note that the reported findings are based on the analysis of data sets that have not passed through a duplicate or triplicate review. That review of data should be completed before the results are considered final.

As mentioned previously, there are positive offsets that can reduce total emissions. These offsets include energy recovery, carbon sequestration, and recovery of important soil nutrients, such as nitrogen and phosphorus to produce fertilizers.

With regard to energy recovery, there are significant opportunities from wastewater treatment facilities, anaerobic digestion, and landfilling. Some state and local agencies have tried to trim carbon footprints by maximizing the recovery of valuable outputs, such as this capturing of heat and electricity from biogas generation rather than releasing directly to the atmosphere. While these processes can still have negative environmental impacts, they can reduce reliance on the energy grid with substantial cost benefits. Delaware’s Solid Waste Authority has teamed up with wastewater treatment facilities to establish a renewable energy project that converts two sources of biogas (wastewater treatment and landfill) into power and heat for the treatment plant (Honeywell, 2012).

Other waste management processes can promote carbon sequestration and even help recover important soil nutrients, such as nitrogen and phosphorus, which can be used as fertilizers.

Furthermore, the data within this life cycle assessment do not illustrate the many social and economic implications of food waste management strategies that must be taken into context depending on factors such as available technology alternatives, logistical constraints, environmental hazards, regulatory oversight, and seasonal waste stream composition and supply.

There can also be negative impacts related to the various pathways that are hard to quantify. For instance, while composting provides a relatively low net environmental impact based on the four impact categories in this analysis, composting facilities can be severely compromised by odor complaints in the case of poor management. Food waste handling at Wilmington, Delaware’s Pigeon Point Composting Facility came to a halt in 2014 as management struggled to meet economic targets due to low volumes of contaminated organic waste entering the facility, followed by odor complaints that were never resolved (Seldman, 2014). The Wilmington example illustrates some of the hidden challenges, despite a perceivably environmentally beneficial process.

Finally, the negative impact of rapidly outgrowing available landfill area is a major challenge. An estimated 70 million tons of food waste and yard trimmings entered landfills across the United States in 2014 (USEPA, 2016). Delaware’s Solid Waste Authority reported that while food waste generation continues to increase, low recovery rates have seen only small gains (DSM Environmental, 2016). According to the Environmental and Energy Study Institute, “landfills are the third largest source of anthropogenic methane in the United States” (EESI, 2013). The U.S. Environmental Protection Agency reports that landfill gas comprises 14.1 percent of all US methane emissions (USEPA, 2018). Limited space, high tipping fees, regulatory support, and an increasing environmental conscious will, hopefully, continue to push waste producers to seek innovative ways to reduce environmental footprints in our age of growing consumption.

Appendix D: Additional Factors for Consideration for Each Pathway

The following is a discussion of additional factors that could be considered for each disposal pathway. In some cases these considerations result from limited information, while in other cases they result due to the qualitative rather than quantitative nature of the issue.

Aerobic digestion to wastewater treatment facility: Discharging of digestate to the sewer system is a simple management option that takes advantage of the existing wastewater treatment infrastructure for diverting food waste from landfills. In our analysis, we estimated the global warming potentials (GWP) of 1,000 kg food waste discharged through an aerobic digester and a "generic" wastewater treatment plant (WWTP). However, greenhouse gas production from WWTPs may be strongly influenced by the types of treatment plants and wastewater characteristics. In order to more accurately estimate GWP of a WWTP, various factors such as emissions from individual unit processes and strength/type of influent need to be considered. In addition, the potential to discharge the digestate to WWTPs may be limited by the capacity of the sewer system and the ability of the WWTP to handle and treat additional flow with a high biological oxygen demand (BOD). On the other hand, for treatment plants with anaerobic digestion, the addition of organic-rich digestate in their influent can enable these plants to approach "energy neutrality" and some to become "energy positive" due to the increased biogas production. Fats, oil, and grease (FOG) commonly present in food waste have been reported to enhance biogas production from anaerobic digesters at WWTPs. The addition of readily available high strength organic wastes in the influent may also serve as valuable carbon resources to biological nutrient removal (BNR) WWTPs. With the nutrient discharge standards becoming more stringent, external carbon compounds (e.g., methanol, ethanol, acetate, etc.) are often added to the influent to improve the efficiency of nitrogen and phosphorus removal by BNR plants. The addition of organic-rich digestate to the influent may not only increase nitrogen and phosphorus removal performance of WWTPs but may also reduce the requirement of external carbon supplementation.

Aerobic digestion to anaerobic digestion: Anaerobic digestion has long been perceived as a net-beneficial waste management process, particularly for manure management applications, however, there are challenges to this perception (USDA, 2018). Other available waste treatment alternatives may be dismissed despite lower costs and comparable environmental benefits, and depending on the technology employed, the emissions released in biogas-to-energy conversion can outweigh the net benefit of digestion. In our analysis, we estimated the that 1,000 kg of food waste could produce a net benefit of 175 kWh generated from the Aerobic-AD process. Ultimately, we are reminded that there is a great deal of variability in digestion technologies that must be carefully evaluated to ensure the waste management process provides an environmentally sound alternative in its particular application. When it comes to fine tuning the pre-treatment of anaerobic digester influent, such as through aerobic digestion, further research is recommended to evaluate the optimal influent compositions influencing the quality of the effluent. These treatment options present an ideal alternative to manage multiple waste streams for energy recovery.

Trash bag to landfill: In addition to emissions of greenhouse gases from landfilled food waste and transport emissions, the potential for accidents and spills present concerns about the environmental and human health risks of collecting and trucking food waste to the landfill. In some cases, the food waste is collected in a centralized location and transported long distance to the landfill by long-haul trucks, resulting in additional financial burden on municipalities for the operation and maintenance of large garbage trucks.

Trash bag to composting facility: Disposal of food waste to a compost facility has the potential to convert organic material to high-value compost for return to the soil. However, common challenges include odor complaints and lack of end market for compost. In addition, the off-site migration of runoff from compost facilities often cause environmental problems which can require collection and treatment.

Appendix E: References

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