ENERGY BALANCE AND NUTRIENT REMOVAL IMPACTS OF FOOD WASTE DISPOSERS ON WASTEWATER TREATMENT

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Abstract

The concurrent megatrends of diversion of organics from landfills and resource recovery at wastewater treatment plants position food waste disposers as important potential tools for municipal authorities. The additional organic loading to treatment plants has historically been viewed as burdensome, but given the actual characteristics of food waste, especially the high carbon to nitrogen and phosphorus ratio, based on BioWin modeling of three types of wastewater treatment processes, there are overlooked benefits from more extensive use of disposers, including a net energy gain from combined heat and power systems utilizing biogas, and improved nutrient removal for plants striving for lower effluent limits.

Keywords

Anaerobic digestion , activated sludge, Bardenpho, biogas, co-digestion, food waste disposer, Modified Ludzack-Ettinger, nitrification.

Introduction

In urban areas, food waste may be managed through onsite composting, landfilling, codigestion, or wastewater treatment via disposers. A graphical comparison of strategies for food waste management is presented in Figure 1.

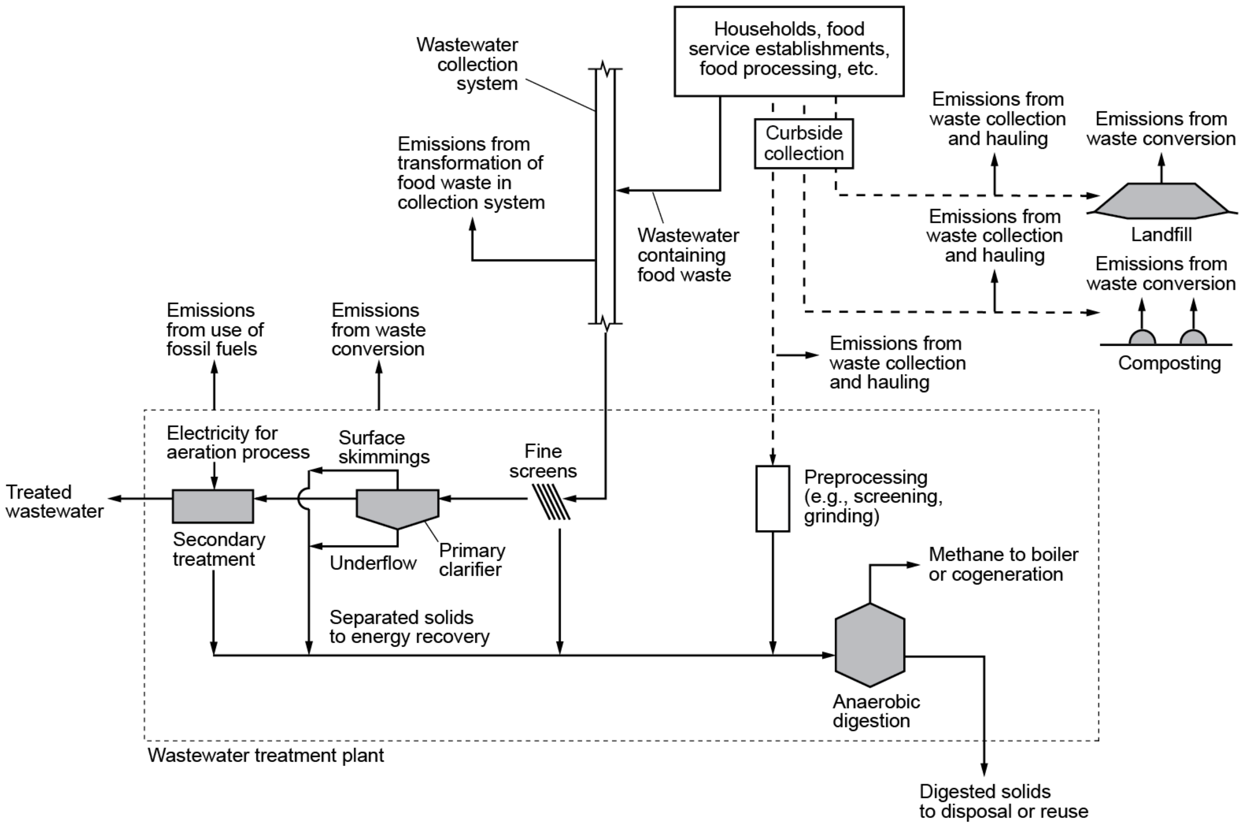

Figure 1: Alternative management strategies for food waste in urban systems.

Food Waste Properties Relevant To Wastewater Treatment

Generation of Food Waste

The estimated generation rate of residential food waste is 0.3 kg/cap·d (wet basis) (Diggelman and Ham, 1998; Tchobanoglous et al., 1993). The amount of food waste total solids (TS) resulting from kitchen sinks and dishwashers is about 0.07 kg/cap·d (wet basis) while the amount processed through FWDs, where they are used in conjunction with other food waste management options (i.e., not mandated or used exclusively), is about 0.1 kg/cap·d (wet basis). The food waste discharge to wastewater at an assumed moisture content of 70 percent, with and without a FWD, can be computed as follows:

Food waste TS in wastewater without FWD (i.e., kitchen sink, dishwasher)

= (0.07 kg/cap·d)(0.3) = 21 g/cap·d (dry basis)

Food waste TS in wastewater with FWD (i.e., kitchen sink, dish washer, FWD)

= (0.17 kg/cap·d)(0.3) = 51 g/cap·d (dry basis)

The addition of a FWD will therefore increase the discharge of food waste TS by about 30 g/cap·d (dry basis). The fraction of food waste TS is present as suspended solids (TSS), without and with a FWD, is estimated to be 21 and 35 percent, respectively (Diggelman and Ham, 1998).

Food waste TSS in wastewater without FWD (i.e., kitchen sink, dishwasher)

= (21 g/cap·d)(0.21) = 4.5 g/cap·d (dry basis)

Food waste TSS in wastewater with FWD (i.e., kitchen sink, dish washer, FWD)

= (51 g/cap·d)(0.35) = 18 g/cap·d (dry basis)

When diluted with residential greywater at a rate of about 350 L/cap·d, the increase in wastewater TSS is estimated as follows:

Incremental change in TSS with 100 percent FWD use

= (18 - 4.5 g/cap·d) / (350 L/cap·d) = 39 mg/L

It is expected that the increased TSS loading resulting from use of FWD will be partially removed in the primary clarifier and, where available, processed subsequently in an anaerobic digester or waste to energy facility. In some cases, the soluble and colloidal fraction of food waste that passes through primary treatment has been found to have a positive impact on the removal of nitrogen and phosphorus from wastewater (Battistoni et al., 2007, Evans et al., 2010). Therefore, it has been hypothesized that food waste can be a beneficial carbon source in municipal wastewater treatment systems.

Characteristics of Food Waste

The characteristics of food waste most relevant to wastewater treatment operations include the organic, particulate, and nutrient fractions. In particular, the total COD content and the COD to N ratio of food waste are of importance in biological nutrient removal (BNR) systems. The COD to N ratio, based on molecular weight (MW) and derived from the chemical formula for food waste (Tchobanoglous et al., 1993), is determined by writing a balanced reaction for the oxidation of food waste, as shown in Eq. (1):

$$\underset{511.37}{C_{21.53}H_{34.21}O_{12.66}NS_{0.07}} + \underset{23(32)}{23O_2} \rightarrow 21.53CO_2 + NH_3 + 15.61H_2O \quad (1)$$

Phosphorus (P) is not included in the empirical chemical formula presented in Eq. (1) because it is a relatively minor constituent. Based on a typical N to P weight ratio of 8, the chemical formula can be rewritten $C_{21.53}H_{34.21}O_{12.66}NS_{0.07}P_{0.056}$, which would also increase the formula weight to 513 g/mole.

The corresponding COD to nitrogen ratio is shown in Eq. (2):

$$COD / N = [23\ (32\ g\ O_2/mole)] / (14\ g\ N/mole) = 53 \quad (2)$$

A comprehensive study of food waste composition was conducted by InSinkErator (2010) by grinding what is considered to be a food waste stream typical of the diet in the United States. The processed food waste was then evaluated for standard wastewater constituents. The results of the food waste grinding experiments normalized to food waste dry weight and estimated loading rate are presented in Table 1. It should be noted that, in the case of the data presented in Table 1, food waste grinding resulted in about 41 percent of total food waste being converted to particulate matter (TSS) and the remaining fraction would be the dissolved or soluble component. Assuming primary treatment is used, the soluble fraction would be available for use in wastewater treatment.

Table 1: Example wastewater constituent data for typical food stream after processing with a FWD based on 20 samples (ISE, 2010).

	Value (dry basis)	
Constituent	g/kg food waste[a]	g/capita·d[b]
COD	1155	34.6
BOD	533	16.0
Sol BOD	312	9.4
TSS	409	12.3
O&G	323	9.7
TKN	21.3	0.64
TP	2.8	0.08
S	3.5	0.11

[a] Dry basis, food waste TS was 17 percent
[b] Based on per capita food waste generation of 30 g/capita·d (dry basis)

The data presented in Table 1 are compared to results obtained from other studies in Table 2. The COD to TKN ratio of the wastewater given in Table 2, which does not include FWD use, is 14; with FWD use the ratio is increased to 15.8. The COD to N ratio of the discharge collected from the FWD alone is 54, which is in agreement with the ratio computed using Eqs. (1) and (2). Given that this ratio is considered to be typical based on field measurements, it can also be used to screen mass loading data for accuracy. As discussed in Sec. 6, the relatively high COD content of food waste is an important factor in the utilization of food waste as a carbon source for nutrient removal in wastewater treatment.

Table 2: Mass loading data from various studies

Parameter	Constituent mass loading for typical wastewater[a], g/capita-d	Mass loading of constituents from FWDs as reported in various studies, g/capita-d			
		Diggelman and Ham, 1998	de Koning and van der Graaf, 1996	ISE, 2010	Typical
TSS	70	18	48	12	15
TS		30		17	25
TVS		23			
VSS		17			
BOD	70	18	52	16	18
BOD (filtered)				9.4	10
COD	180	35	76	35	35
TKN	13	0.5	1.6	0.64	0.6
TP	2.1	0.1		0.08	0.1
COD:TKN	14	70	48	54	58
COD:TP	86	350		440	350

[a]From Tchobanoglous et al., 2013.

Energy Content of Food Waste

The energy content of food waste can be estimated from an elemental analysis of the constituents in organic compounds using the following expression, which is a modified form of the DuLong formula developed by Channiwala (1992):

$$\text{HHV (MJ/kg)} = 34.91\text{ C} + 117.83\text{ H} - 10.34\text{ O} - 1.51\text{ N} + 10.05\text{ S} - 2.11\text{A} \quad (3)$$

Where HHV is the high heating value and C is the weight fraction of carbon; H of hydrogen; O of oxygen; N of nitrogen S of sulfur, and A of ash as derived from an ultimate analysis or from the chemical formula, if known. The formula used most commonly for food waste is $C_{21.53}H_{34.21}O_{12.66}NS_{0.07}$ with an ash content of 5.0 percent. A step-wise process to estimate the energy value of food waste is presented below.

1. Determine the energy content of wastewater using Eq. (3)

    a. Determine the weight fractions of the elements and ash comprising the wastewater.

Component	Coefficient	Molecular weight	Molecular mass	Weight fraction
Carbon	21.53	12	258.36	0.480
Hydrogen	34.21	1	34.21	0.064
Oxygen	12.66	16	202.56	0.376
Nitrogen	1	14	14	0.026
Sulfur	0.07	32	2.24	0.004
Ash	0	0		0.050
			511.37	1.00

[a](94.8/182.28) x 0.97 = 0.50

b. The energy content of the organic fraction using Eq. (3) is:

HHV (MJ/kg organic fraction) = 34.91 (0.480) + 117.83 (0.064) - 10.34 (0.376) - 1.51 (0.026) + 10.05(0.004) - 2.11 (0.05)

HHV (MJ/kg organic fraction) = 16.76 + 7.49 – 3.89 – 0.039 + 0.042 – 0.106 = 20.25

2. Determine the COD of the organic fraction

a. Write a balanced reaction for the chemical oxidation of the food waste (neglecting sulfur)

$C_{21.53}H_{34.21}O_{12.66}NS_{0.07} + 23O_2 \rightarrow 21.53CO_2 + NH_3 + 15.61H_2O$

511.37 23(32)

b. The COD of the organic fraction is:

COD = 23(32 g O_2/mole)/(511.37 g organic fraction /mole) = 1.44 g O_2/g organic fraction

3. Determine the energy content of the food waste in terms of MJ/kg COD

HHV (MJ/kg organic fraction COD) = (20.25 MJ/kg of organic fraction)/(1.44 kg O_2/kg organic fraction)

= 14.06 MJ/kg organic fraction

Using the conversion factor of 3.6 MJ/kWh, food waste energy potential is about 3.9 kWh/kg COD, which is estimated to be about 5600 kWh/MT dry food waste [(1.44 g COD / g food waste) x 3900 kWh/MT].

Technical Issues in Food Waste Grinding

Food waste grinders are used to reduce the size of food waste (as generated) to a size that can be transported using existing wastewater collection systems (ASSE, 1989; AHAM, 2009). In assessing the potential impacts of food waste grinders on wastewater systems, a number of factors related to the efficacy of food waste grinders are presented in this section, including particle size, power consumption, and water use.

Particle Size Analysis

Food waste grinders process food using a set of rotating lugs that macerate food waste before it is discharged to the wastewater collection system. The particle size distribution resulting from the grinding operation depends on a number of factors, including the type of food waste, design of the grinder, and motor power (Kegebein et al., 2001). Example particle size distributions resulting from grinding of food waste using a domestic food waste grinder are shown on Fig. 2. With essentially all food waste reduced to less than 10 mm. A portion of the food waste, estimated to range from less than 0.1 percent for hard materials to more than 60 percent for readily soluble materials, is able to pass through a standard TSS filter. The particle size distribution of food waste after grinding is important because of the fate of this biodegradable particulate and soluble material during wastewater management.

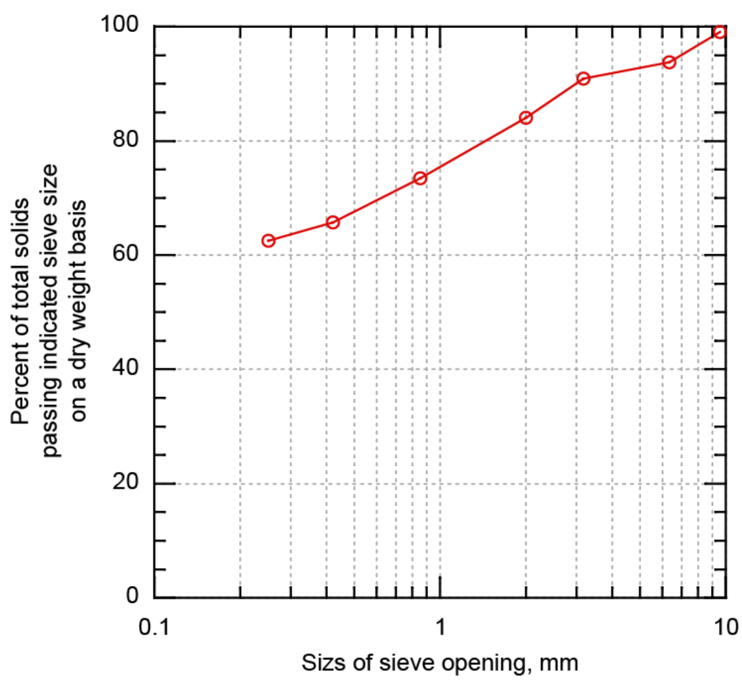

Figure 2: **Particle size distribution of mixed food waste following grinding in a domestic food waste grinder (data from Baumann et al., 1955).**

Energy Consumption

A rough estimate can be obtained by assuming that the power draw for a typical FWD is 1000 W and that the device is used daily for approximately 30 s per person. The estimated power consumption for FWDs is estimated as follows:

$$\text{Power consumption} = (1\ \text{kW})(0.5\ \text{min/capita}\cdot\text{d}) / (60\ \text{min/h}) = 0.008\ \text{kWh/capita}\cdot\text{d}$$

Based on several studies that have tracked the actual consumption of power from FWDs, a reasonable estimate of power usage is 4 kWh/home·yr. For a community with a flowrate of 10 Mgal/d (about 130,000 people and 50,000 FWDs), the total power consumption for 100 percent usage is estimated to be 200,000 kWh/yr, or 560 kWh/d. For the 50 percent usage scenario, the power usage for food waste grinding would be half, or 280 kWh/d.

Water Use

Similarly water use can be estimated to be less than 1 gal/capita·d, and has been measured at 0.8 to 1.6 gal/home·yr (Karlberg and Norin, 1999). For a community with a wastewater flowrate of 10 Mgal/d and 50,000 FWDs, the increase in flow would be approximately 75,000 gal/d. Water use is therefore insignificant as it represents less than 1 percent of residential usage.

Energy Recovery From Food Waste

Anaerobic digestion facilities exist at many wastewater treatment facilities because of the improved quality and dewaterability of digested biosolids. For anaerobic digestion, the particulate fraction of food waste present in untreated wastewater must first be separated from the bulk flow. A number of technologies exist to facilitate solids separation, including sedimentation, screening, and flotation. The topics covered in this section include primary removal rates of food waste, an biogas generation based on the chemical formula of food waste, and observed values of energy recovery from food waste using anaerobic digestion.

Strategies for Food Waste Recovery from Wastewater

The most common unit processes applied for the removal of suspended matter from wastewater are primary clarifiers. The efficiency of solids removal using primary clarifiers is typically about 65 percent. However, based on past experience, about 90 percent of food waste TSS can be removed using a primary clarifier (Gonwa, 2010). It is likely that advanced primary and charged bubble flotation, described below, could be used to capture essentially all particulate food waste (40 percent of total).

While it is clear that wastewater systems can be optimized to remove the particulate fraction of food waste, even typical primary clarification facilities will provide adequate treatment.

Theoretical Biogas Generation from Food Waste

The amount of biogas that can be produced from food waste can be estimated based on an analysis of the chemical formula of a composite sample. The chemical formula that is used commonly is $C_{21.53}H_{34.21}O_{12.66}NS_{0.07}$ (Tchobanoglous et al., 1993). The computation steps are presented below:

1. Using the chemical formula $C_{21.53}H_{34.21}O_{12.66}NS_{0.07}$, estimate the amount of methane and carbon dioxide that can be produced using the formula.

$$C_aH_bO_cN_d + [(4a-b-2c+3d)/4]H_2O \rightarrow [(4a+b-2c-3d)/8]CH_4 + [(4a-b-2c+3d/8)]CO_2 + dNH_3$$

For the given formula,

a = 21.53   b = 34.21   c = 12.66   d = 1

The resulting equation is

$$C_{21.53}H_{34.21}O_{12.66}N_1 + 7.40H_2O \rightarrow 11.50CH_4 + 10.03CO_2 + 1.00NH_3$$

511.4   133.2   184.0   441.3   17

2. Determine the weight fraction of methane and carbon dioxide from the equation derived in Step 1.

Methane = 184.0/511.4 = 0.36 kg/kg

Carbon Dioxide = 441.3/511.4 = 0.86 kg/kg

3. Convert the weight of gases, determined in Step 2, to volume, using the following specific weights for methane and carbon dioxide, 0.7167 kg/m^3 and 1.9768 kg/m^3, respectively.

Methane = (0.36 kg/kg)/(0.7167 kg/m^3) = 0.50 m^3/kg

Carbon Dioxide = (0.86 kg/kg)/(1.9768 kg/m^3) = 0.44m^3/kg

4. Determine the percentage composition of the resulting gas mixture.

Methane % = (0.50)/(0.50 + 0.44) = 53.2%

Carbon Dioxide = 46.8%

The theoretical biogas production is 940 m^3/MT (dry basis). Assuming solids content is 0.3, the theoretical biogas production is 282 m^3/MT (wet basis). As discussed below, observed biogas production values are about 72 percent of the theoretical value.

Observed Parameters for Anaerobic Digestion of Food Waste

Several studies have been conducted to determine the parameters relevant to biogas generation from food waste digestion. The data from these studies are summarized in Table 3. To compare the biogas yield values with the theoretical value computed in the previous section, the values computed above should be multiplied by 0.9 and 0.8 to account for the ash content and VS destruction, respectively, resulting in an adjusted theoretical estimates of 677 m^3/MT (dry basis) and 203 m^3/MT (wet basis), which are somewhat higher than the measured values reported in Table 3.

The energy value of food waste computed in Sec. 2 was determined to be about 5600 kWh/MT dry food waste. The electrical energy value (reported at kilowatt hour electric, kWhe) observed in the field using anaerobic digestion is 1100 kWhe/MT dry food waste. Therefore, the efficiency of converting the potential chemical energy contained in food waste to electrical energy is estimated to be 20 percent.

Table 3: **Observed values from food waste digestion studies[a].**

Parameter	Unit	Range	Typical
TS	Percent	25 – 28	27
Methane content	Percent	64 - 75	70
VS/TS	Percent	86 - 95	90
VS destruction	Percent	74 - 82	80
Biogas yield	m^3/MT (wet)	150 -160	157
	m^3/MT (dry)	500 - 650	600
Methane yield	m^3/MT (wet)	100 - 120	110
	m^3/MT (dry)	375 - 450	420
Energy production[b]	kWhe/MT (wet)	270 - 300	280
	kWhe/MT (dry)	900 – 1200	1100

[a] Adapted from Kennedy Jenks (2009), EBMUD (2008), Zhang et al. (2005), Cho et al. (1995).
[b] Based on assumed generator electricity output of 1.8 to 2 kWhe/m^3. Total energy content of biogas is reported to range from 5.5 to 8 kWh/m^3, depending on methane content. The heat output from cogen is assumed to be used for digester heating and therefore not accounted for as an energy output.
However, about 4 to 5 kWh of heat would be obtained per m^3 of biogas input to cogen.

Utilization of Food Waste in Wastewater Treatment

Many studies have found minimal impact on municipal wastewater systems when food waste disposers (FWDs) are implemented (Evans et al., 2010). In some cases, improvements have been recorded with respect to nutrient removal when food waste is blended into the wastewater stream (Battistoni *et al.,* 2007).

In this present study, a wastewater process modeling approach has been used to evaluate the potential impacts of FWDs on three alternative wastewater treatment systems. The types of wastewater treatment systems considered in this report include:

- Activated sludge (AS) with nitrification and anaerobic digestion (AD)
- Activated sludge with nitrified mixed liquor recycle and AD (i.e., Modified Ludzack-Ettinger, MLE)
- Biological nutrient removal (BNR) with primary solids fermentation and AD (i.e., 5 stage Bardenpho)
-

The models evaluated in this study encompass the majority of municipal wastewater treatment facilities used currently in Europe and North America, with a greater shift toward BNR processes anticipated in the near future ((Henze et al., 2008; Oleszkiewicz and Barnard, 2006). The data presented below includes an assessment of constituent mass loading to wastewater from alternative fixtures, presentation of data used for process modeling, and model results for each of the three wastewater systems.

Data Used for Influent Modeling

The influent chemical characteristics used in the wastewater process modeling are presented in Table 4, with the constituent concentrations reported as a percentage of FWD utilization at 0, 10, 50, and 100 percent. The changes in constituent concentration that occur with increased FWD usage were computed using the data presented in Table 2 assuming a total water usage of 75 gal/capita·d. Because of the site specific nature of wastewater collection systems, decomposition of wastewater constituents during collection and transport were not considered.

Table 4: Influent data used for wastewater process modeling[a].

		FWD utilization, percent			
Parameter	Unit	0	10	50	100
Flowrate	Mgal/d	10	10	10	10
COD	mg/L	438	451	500	562
cBOD	mg/L	230	236	267	304
TKN	mg/L	43.0	43.2	44.1	45.1
TP	mg/L	8.30	8.33	8.44	8.59
Nitrate	mg N/L	0	0	0	0
pH		7.3	7.3	7.3	7.3
Alkalinity	mmol/L	6	6	6	6
TSS	mg/L	189	194	211	243
Inorganic SS	mg/L	31.0	31.4	32.8	34.6
Calcium	mg/L	80	80	80	80
Magnesium	mg/L	15	15	15	15
Dissolved oxygen	mg/L	0	0	0	0

[a] Concentrations computed assuming per capita water usage of 280 L/d.

Model Results and Energy Implications

Model results are provided for the steady-state simulation approach for process parameters (i.e., modeling results) and projected energy impacts (i.e., energy implications). The air supply is the amount of air that would need to be delivered to the aeration basin to meet the biological process demands. The mixed liquor suspended solids (MLSS) and solids retention time (SRT) are variables used to characterize the biological process. Digester gas output is the amount of biogas that would be produced using a mesophilic anaerobic digester with 20 d SRT processing solids from the primary and secondary processes. Digested solids are reported on a dry mass basis. The effluent BOD, TN, and TP are the expected effluent values following secondary clarification.

For purposes of the energy balance calculations, it is assumed that 860 kWhe/d will be required to supply an additional 1000 ft^3/min of air to the aeration basins. Similarly, electricity production from biogas production is estimated at 80 kWhe/d for every additional 1 ft^3/min of increased biogas output. The computations used to estimate energy for aeration and from biogas conversion are included in Appendix A.

Activated Sludge (AS) with Nitrification Model

The conventional AS model shown in Fig. 4 includes primary settling, aerobic oxidation, and secondary settling. Waste activated solids (WAS) are processed by thickening. Thickened WAS and primary solids are added to the anaerobic digester for stabilization. Digested solids are dewatered and return flows are discharged to the aeration tank.

Modeling results

The results of the modeling are presented in Table 5. It should be noted that positive energy values are indicative of an increase in energy consumption, and negative values are used for a reduction in energy consumption. As shown in Table 5, the increased contribution of food waste from FWD at 50 percent usage increases the aeration demand [8.7 percent; e.g., (10,173 – 9361) / 9361], biosolids production (9.7 percent), and digester gas output (15.8 percent). However, the change in effluent concentration of BOD, total N, and total P are negligible.

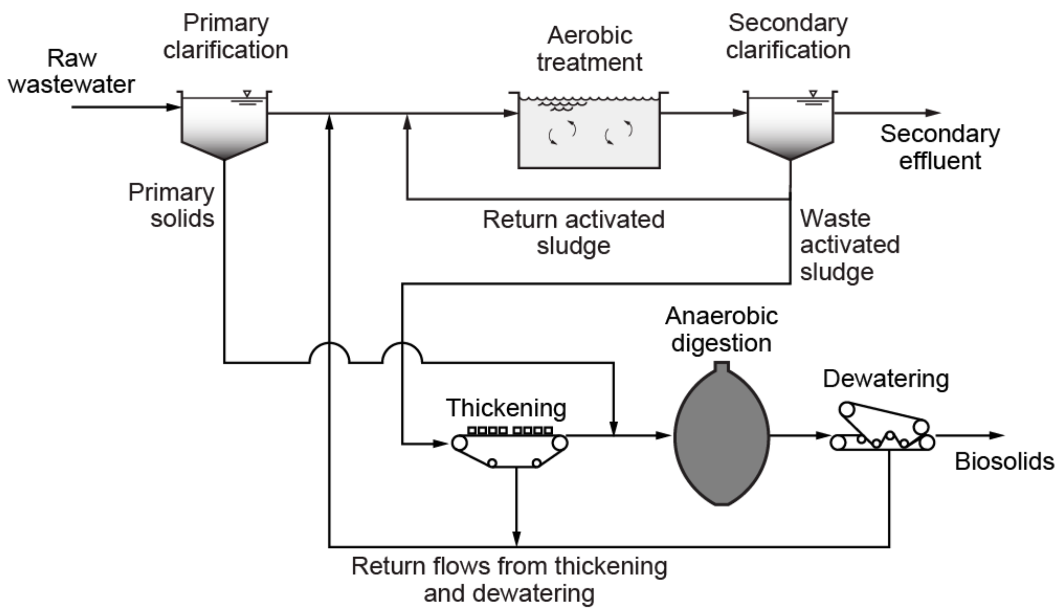

Figure 4: Flow diagram used for simulation of conventional AS process with nitrification.

Energy implications

An increased aeration demand will result in additional power consumption by process blowers to supply oxygen to the biological process. To maintain a dissolved oxygen (DO) concentration of 2 mg/L at 50 percent FWD usage, and assuming 860 kWhe/d to supply 1000 ft^3/min of air, an additional 698 kWhe/d would be needed. However, anaerobic digestion of waste activated sludge and the particulate fraction removed in primary clarification, followed by electricity production at a rate of 80 kWhe/d for every 1 ft^3/min of increased biogas output, results in recovery of 1200 kWhe/d for the 50 percent FWD scenario. The net increase in electricity production is estimated to be 502 kWh/d. A significant amount of heat energy would also be produced using cogeneration, which could be used for digester heating and other process heat demands, but is not accounted for in this analysis. As discussed in Sec. 3, the power to operate the FWDs for the 50 percent scenario is estimated to be 280 kWh/d, resulting in an overall net increase in energy recovery for the activated sludge with nitrification model. For the activated sludge with internal recycle of nitrified mixed liquor, the addition of food waste could reduce the amount of aeration required and reduce effluent nitrogen concentrations.

Table 5: Steady-state simulation data for conventional AS with nitrification scenario.

		Percent of FWDs in use[a]			
Parameter	Unit	0	10	50	100
		Process data			
Primary clarifier					
TSS removal	%	65	65	65	65
Biological treatment					
Temperature	deg C	20	20	20	20
HRT	h	3.6	3.6	3.6	3.6
Dissolved oxygen	mg/L	2.0	2.0	2.0	2.0
Alpha	-	0.5	0.5	0.5	0.5
RAS flowrate	-	1Q	1Q	1Q	1Q
		Modeling results			
Air supply	ft^3/min	9361	9530	10,173	11,146
MLSS	mg/L	1961	2014	2214	2476
SRT	d	3.0	3.0	3.0	3.0
Digester gas	ft^3/min	95	98	110	124
VSS destruction	percent	61	61	61	61
Digested biosolids	lb/d (dry)	8999	9213	9873	10,761
Effluent BOD	mg/L	6.4	6.5	7.0	7.6
Effluent total N	mg/L	35.9	35.8	35.9	35.9
Effluent total P	mg/L	6.5	6.5	6.4	6.3
		Energy implications			
Aeration energy	kWhe/d	-	+ 145	+ 698	+ 1535

Biogas conversion	kWhe/d	-	- 240	- 1200	- 2320
Total energy impact	kWhe/d	-	- 95	- 502	- 785

[a] Assumed electrical energy demand for aeration is (0.86 kWhe/d) / (ft^3/min)
[b] Assumed electrical energy recovery from biogas is (80 kWhe/d) / (ft^3/min)

Activated Sludge with Nitrified Mixed Liquor Recycle Model

The activated sludge model with internal recycle of nitrified mixed liquor to an anoxic stage, commonly known as the Modified Ludzack-Ettinger (MLE) process is shown in Fig. 5 and includes primary settling, anoxic denitrification, aerobic oxidation, and secondary settling. An internal recycle flow is included to enhance nitrogen removal. Waste activated solids are processed by thickening. Thickened WAS and primary solids are stabilized using anaerobic digestion. Digested solids are dewatered and return flows are discharged to the aeration tank.

Modeling results

As shown in Table 6, the increased contribution of food waste from FWDs has a minor impact on the aeration demand at the 50 and 100 percent FWD level. As in the previous case, there is an increase in biosolids and biogas production, but there is little change in the effluent concentration of BOD and total P. A reduction in total N (up to 32 percent) is expected as the amount of food waste from FWDs is increased. In cases that are carbon limited, the addition of food waste at the anoxic stage will result in a reduction in the effluent total N concentration.

Energy implications

For this scenario, there is a relatively small change in aeration energy requirements, including the case of 100 percent FWD usage. However, anaerobic digestion of waste activated sludge and the particulate fraction removed in primary clarification, followed by electricity production, results in the recovery of 960 kWhe/d for the 50 percent FWD scenario. A key finding for the activated sludge with internal recycle of nitrified mixed liquor scenario is that the addition of food waste has a minimal impact on the amount of aeration required because the additional carbon load is consumed as a result of denitrification.

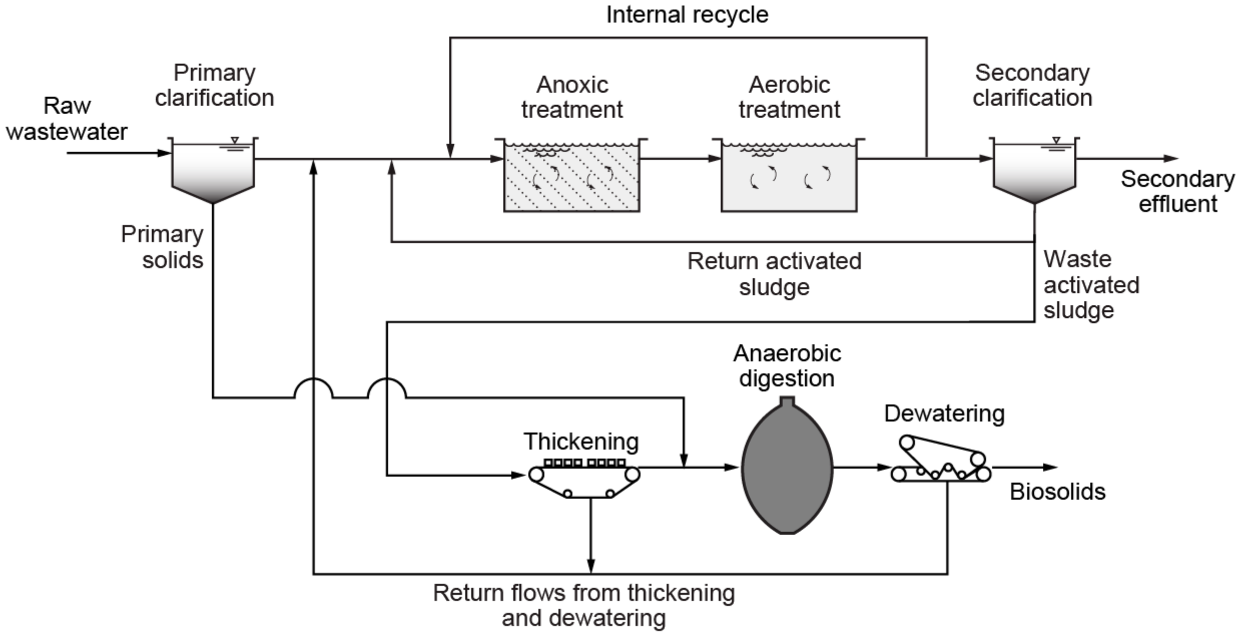

Figure 5: Flow diagram used for simulation of the activated sludge with recycle of nitrified mixed liquor process.

Table 6: Steady-state simulation data for activated sludge with recycle of nitrified mixed liquor scenario.

Parameter	Unit	Percent of FWDs in use[a]			
		0	10	50	100
		Process data			
Primary clarifier					
TSS removal	%	65	65	65	65
Biological treatment					
Temperature	deg C	20	20	20	20
HRT, anoxic	h	7.2	7.2	7.2	7.2
HRT, aerobic	h	9.6	9.6	9.6	9.6
Dissolved oxygen	mg/L	1.0	1.0	1.0	1.0
Alpha	-	0.5	0.5	0.5	0.5
RAS flowrate	-	1Q	1Q	1Q	1Q
Internal recycle	-	4Q	4Q	4Q	4Q
		Modeling results			
Air supply	ft^3/min	6846	6947	7187	7672
MLSS	mg/L	1518	1555	1641	1966
SRT	d	17.6	17.6	17.6	17.6
Digester gas	ft^3/min	86	89	98	111
VSS destruction	percent	65	65	65	65
Digested biosolids	lb/d (dry)	7391	7544	7898	8621
Effluent BOD	mg/L	3.1	3.2	3.3	3.8
Effluent total N	mg/L	13.0	12.3	8.9	8.9
Effluent total P	mg/L	7.0	7.0	7.0	6.7
		Energy implications			
Aeration energy[a]	kWhe/d	-	+ 87	+ 293	+ 710
Biogas conversion[b]	kWhe/d	-	- 240	- 960	- 2000
Total energy impact	kWhe/d	-	- 153	- 667	- 1290

[a] Assumed electrical energy demand for aeration is (0.86 kWhe/d) / (ft^3/min)
[b] Assumed electrical energy recovery from biogas is (80 kWhe/d) / (ft^3/min)

BNR Process (5-stage) with Primary Solids Fermentation Model

The 5-stage BNR model, commonly known as the Bardenpho process, shown in Fig. 6 includes anaerobic pretreatment, anoxic denitrification, aerobic oxidation, second-stage anoxic, re-aeration, and secondary settling. Primary sludge fermentation is included to stimulate phosphorus uptake in the aerobic tank, while an internal recycle flow is included to enhance nitrogen removal. Processing of waste activated solids are not considered in this case, but would need to be processed separately, in a side-stream reactor for example, to manage the high phosphorus content of the biomass.

Modeling results

Table 7 shows the increased contribution of food waste from FWDs increases the aeration demand and biosolids production slightly. While there is little change in the effluent concentration of BOD, as the amount of food waste from FWDs is increased, there is a significant reduction in the effluent total N and P concentrations. The reduction in total N and P results from the supplemental carbon available in the anaerobic and anoxic stages. Comparing the three scenarios, the predicted total nitrogen concentration in the effluent will decrease by 7 and 12 percent for 50 and 100 percent FWD utilization, respectively; and total phosphorus will decrease by 52 and 74 percent for 50 and 100 percent FWD utilization, respectively.

Energy implications

As with the previous scenarios, there is a net electricity production when anaerobic digestion is used. However, the overall energy recovery is not as great as in the previous scenario because a greater proportion of the influent carbon is used for nutrient removal.

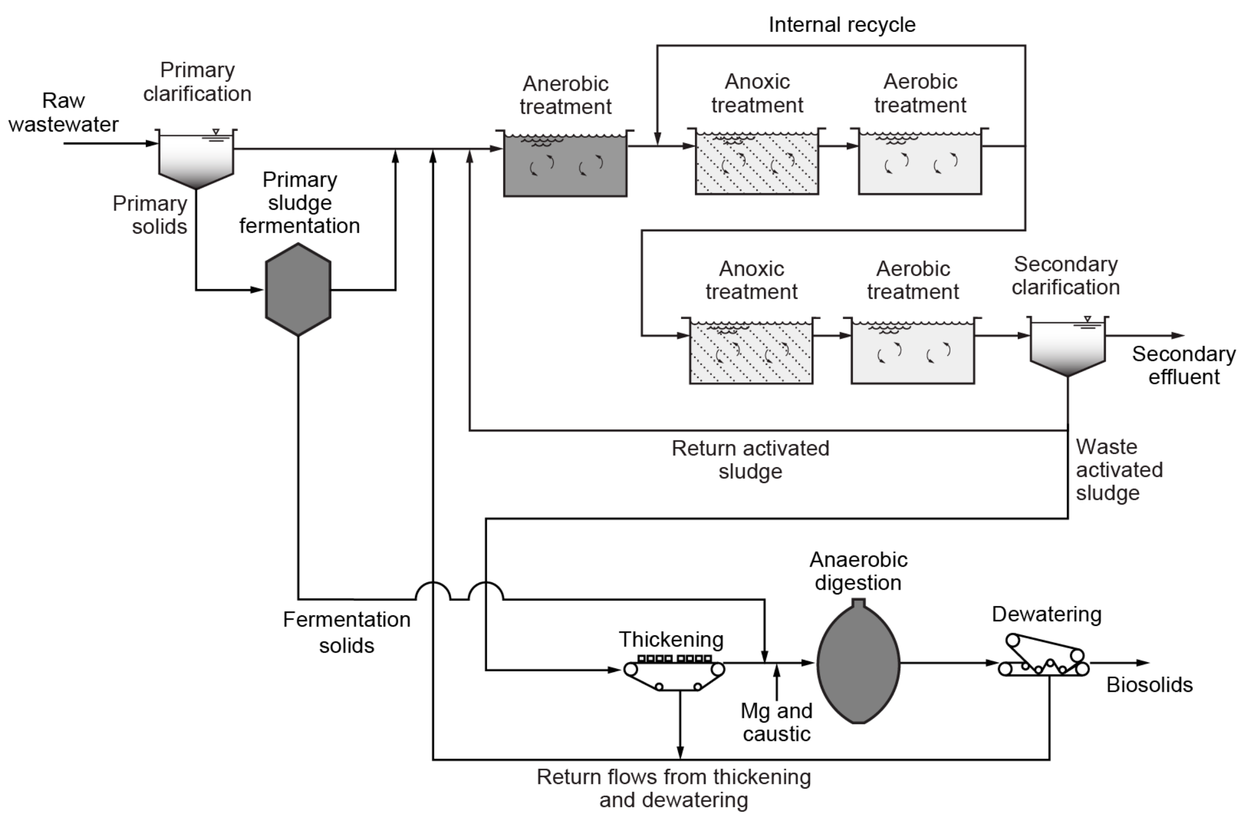

Figure 6: **Flow diagram used for simulation of 5-stage BNR scenario**

Table 7: Steady-state simulation data for 5-stage BNR scenario

Parameter	Unit	Percent of FWDs in use[a]			
		0	10	50	100
		Process data			
Primary clarifier					
TSS removal	%	90	90	90	90
Biological treatment					
Temperature	deg C	20	20	20	20
HRT, anaerobic	h	1.25	1.25	1.25	1.25
HRT, 1st stage anoxic	h	3.6	3.6	3.6	3.6
HRT, 1st stage aerobic	h	7.2	7.2	7.2	7.2
HRT, 2nd stage anoxic	h	3.6	3.6	3.6	3.6
HRT, 2nd stage aerobic	h	0.5	0.5	0.5	0.5
Dissolved oxygen	mg/L	2.0	2.0	2.0	2.0
Alpha	-	0.5	0.5	0.5	0.5
RAS flowrate	-	1Q	1Q	1Q	1Q
Internal recycle	-	2Q	2Q	2Q	2Q
		Modeling results			
Air supply	ft^3/min	7414	7505	7912	8422
MLSS	mg/L	1606	1672	1936	2214
SRT	d	13	13	13	13
Digester gas	ft^3/min	51	53	61	71
VSS destruction	percent	51	51	50	50
Digested biosolids	lb/d (dry)	10,948	11,319	12,529	13,604
Effluent BOD	mg/L	3.8	3.3	3.8	3.9
Effluent total N	mg/L	8.6	8.5	8.0	7.6
Effluent total P	mg/L	2.7	2.4	1.3	0.7
		Energy implications			
Aeration energy[a]	kWhe/d	-	+ 78	+ 428	+ 867
Biogas conversion[b]	kWhe/d	-	- 160	- 800	- 1600
Total energy impact	kWhe/d	-	- 82	- 372	- 733

[a] Assumed electrical energy demand for aeration is (0.86 kWhe/d) / (ft^3/min)
[b] Assumed electrical energy recovery from biogas is (80 kWhe/d) / (ft^3/min)

Summary of Findings

The key findings from the wastewater process modeling with an increasing fraction of food waste from FWD usage are as follows:

- The incorporation of food waste increases the aeration requirements from 5 to 19 percent for 50 and 100 percent use of FWDs, as compared to no FWD use.
- More biogas and biosolids are produced as FWDs usage is increased. The production and utilization of biogas requires an anaerobic digester and suitable energy conversion equipment. Where anaerobic digestion is used, the resulting electrical energy output from a cogeneration system offsets both the increase in electricity for aeration and power to operate food waste grinders by 26 to 730 kWh/d. A summary of the energy balance for the wastewater treatment facility alone and inclusive of energy for in-home food grinding is shown on figure 7.

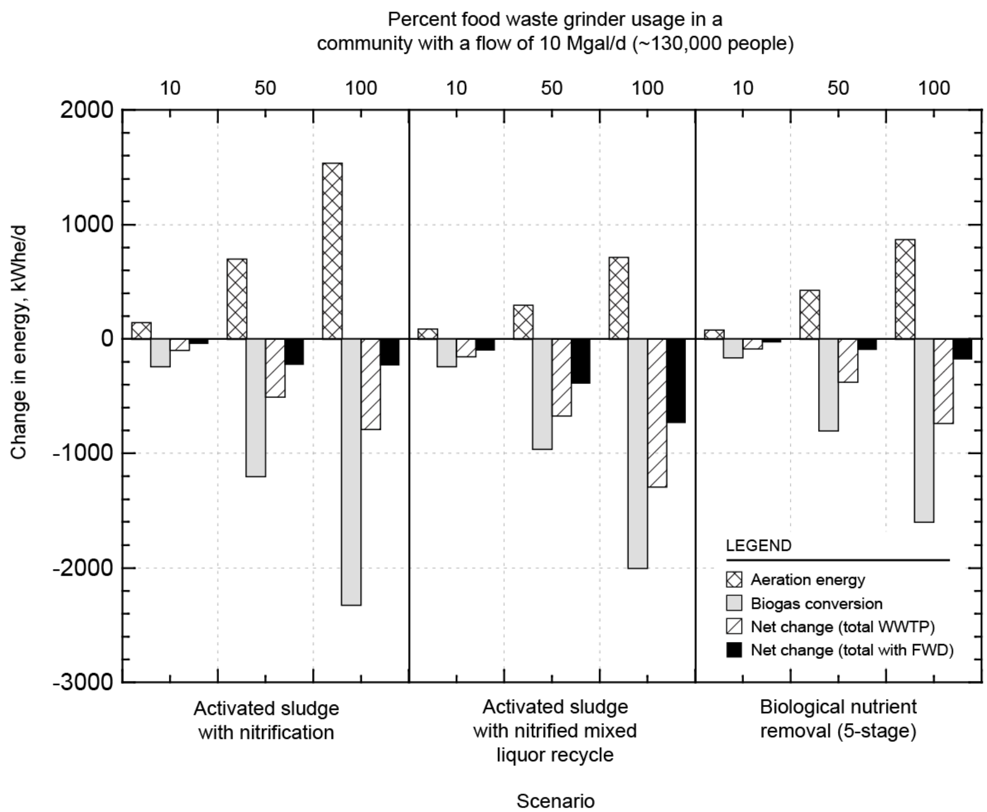

Figure 7: **Summary of energy balance as a function of food waste grinder utilization (positive and negative values represent an increase and decrease in energy usage, respectively).**

- The greatest energy benefit is associated with treatment processes that utilize the carbon content of the wastewater for nitrate removal.
- For the case studies, increased FWD usage has a positive impact on nitrogen and phosphorus removal processes, as characterized by the activated sludge with nitrified mixed liquor recycle and BNR models. Compared to the base case with no FWD usage, TN removal could be increased by 7 and 12 percent for the BNR process with 50 and 100

percent FWD usage, respectively, and TP removal could be increased by 52 and 74 percent in the BNR process with 50 and 100 percent FWD usage, respectively. The implementation of FWD can, therefore, serve as an alternative to the use of external chemical carbon sources, or reduce the amount external carbon needed, for enhanced biological nutrient removal.

- Food waste can be beneficially used as a carbon source for biological nutrient removal and as a substrate for biogas production. The use of high performance primary treatment devices, such as microscreens, primary effluent filtration, and advanced chemical treatment can increase the recovery of the particulate fraction for energy recovery, while the use of primary solids fermentation can enhance the value of food waste as a carbon source.
- The findings from the modeling exercise are consistent with the findings of several controlled field studies that found a positive impact on wastewater treatment systems following the implementation of FWDs.
- Several factors could impact the energy balance and nutrient removal processes occurring at wastewater treatment facilities, such as (a) changes in the particle size distribution and settleable fraction of food waste after grinding; (b) conversion of food waste that takes place in the wastewater collection system; (c) process parameters such as temperature; and (d) site specific factors such as SRT, HRT, and DO monitoring and control.
- The collection of food waste using the existing wastewater collection infrastructure has no known negative consequences, compared to other options for centralized food waste collection. The potential for H_2S production and increased rates for corrosion is site specific and should be evaluated under the specific conditions.
- The processing of food waste at wastewater treatment facilities can result in energy recovery, enhanced nutrient removal, and the recovery of organic matter that can be recycled to agricultural systems.
- The positive impacts of food waste on wastewater treatment systems have not been considered adequately in the life cycle analysis studies that have been conducted to date.
- The 10 percent FWD usage scenario had a net positive impact on the energy balance but was not as significant as the 50 and 100 percent FWD scenarios.
- Site specific modeling will be needed to project the impact of food waste on a particular wastewater treatment systems and optimal utilization of influent food waste.

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