# Critical Thinking Questions – Waste Generation and Characteristics Solutions

## I. Introduction to Waste Generation and Composition

1. Durable and nondurable goods, containers and packaging, food wastes, wood wastes, yard trimmings.

2. Quantifying waste generation is important to: (1) estimate emissions, (2) evaluate waste management-related policies, (3) track resource consumption, (4) determine compliance with federal/state diversion policies, (5) equipment selection, (6) facility design, (7) waste collection system design/planning, (8) city planning, and (9) public works budgeting. Note that additional answers may be provided.

3. (a) top-down approach: using production, import, and export values with estimated product life to approximate generation. The amount of waste landfilled is assumed after estimating recycling, composting, and incineration values.
(b) Middle-up approach: state-level data are aggregated to provide national data.
(c) Facility-based approach (bottom-up approach): aggregating tonnage and material data across the different types of facilities.

4. Greatest: Mississippi; Least: Connecticut.

5. Varies for each state

6. Landfilled

7. When landfill tipping fees are large

8. According to the EPA report, waste recycled/composted is mostly paper and yard trimmings. The waste landfilled is more diverse.

9. Answers will vary, but should include contingencies for identifying the number of loads that should be sorted, the number of categories the waste should be sorted into, the time of year/day the loads should be chosen, how the categories will be weighed, etc.

## II. Generated, Landfilled, and Diverted Wastes

Problem 1:

Assumed Generated Waste: 100 lbs.
Therefore, landfilled waste = 89 lbs. and Recycled Waster = 11 lbs.

| Waste Component | Landfilled % (by wt.)[a] | Landfilled Mass (lb.)[b] | Recycled % (by wt.)[c] | Recycled Mass (lb.)[d] | Generated Mass (lb.)[e] | % Composition of Generated Stream |
|---|---|---|---|---|---|---|
| Food | 8 | 7.12 | 0 | 0 | 7.12 | 7.12 |
| Paper | 28 | 24.92 | 50 | 5.5 | 30.42 | 30.42 |
| Cardboard | 8 | 7.12 | 10 | 1.1 | 8.22 | 8.22 |
| Plastic | 9 | 8.01 | 6 | 0.66 | 8.67 | 8.67 |
| Textiles | 1 | 0.89 | 0 | 0 | 0.89 | 0.89 |
| Rubber | 0.8 | 0.712 | 0 | 0 | 0.712 | 0.712 |
| Leather | 0.8 | 0.712 | 0 | 0 | 0.712 | 0.712 |
| YW | 22 | 19.58 | 8 | 0.88 | 20.46 | 20.46 |
| Wood | 3 | 2.67 | 0 | 0 | 2.67 | 2.67 |
| Glass | 8 | 7.12 | 18 | 1.98 | 9.1 | 9.1 |
| Ferrous Metal | 11.4 | 10.146 | 8 | 0.88 | 11.026 | 11.026 |

Example Calculations:

[a] Given

[b] For food, landfilled mass: $89\ lb \times \frac{8}{100} = 7.12\ lb$

[c] Given

[d] For paper, recycled mass: $11\ lb\ \times \frac{50}{100} = 5.5\ lb$

[e] For paper, generated mass: $24.92\ lb + 5.5\ lb = 30.42\ lb$

[f] For paper, % Composition: $\frac{30.42\ lb}{100\ lb} \times 100 = 30.42$

Problem 2:

First, solve relationship for generated waste:

- Generated = landfilled + recycled
- $G = L + R$
- $R = x \times G$, where 'x' is the specific recycling efficiency
- $G = L + (x \times G)$
- $G = \frac{L}{1-x}$

Next, assume 100 lbs. landfilled and solve for generated mass of each waste component

| Waste Component | Landfilled Waste, % (by wt.)[a] | Recycled Efficiency, %[b] | Mass Landfilled (lb.)[c] | Mass Generated (lb.)[d] | % Comp. of generated waste[e] |
|---|---|---|---|---|---|
| Food Waste | 15 | 0 | 15 | 15 | 6.9 |
| Mixed Paper | 30 | 70 | 30 | 100 | 46 |
| Glass | 7 | 40 | 7 | 12 | 5.4 |
| Plastic | 5 | 50 | 5 | 10 | 4.6 |
| Metal | 3 | 10 | 3 | 3 | 1.5 |
| Textiles | 7 | 0 | 7 | 7 | 3.2 |
| Wood | 8 | 0 | 8 | 8 | 3.7 |
| Yard Waste | 25 | 30 | 25 | 63 | 28.7 |

<u>Example Calculations:</u>

[a] Given

[b] Given

[c] Given

[d] For mixed paper, landfill mass: $100\ lb \times \frac{30}{100} = 30\ lb$

[e] For mixed paper, generated mass: $\frac{30\ lb}{1-0.7} = 100\ lb$

[f] For mixed paper, % Composition: $\frac{100\ lb}{217.5\ lb} \times 100 = 46\ lb$

Problem 3:

Part A:

Generated = landfilled waste + recycled waste
Generated = 150,000,000 lb/yr [given]
Recycled = 30,000,000 lb/yr [$0.2 \times 150{,}000{,}000$]
Landfilled = 120,000,000 lb/yr [150,000,000 – 30,000,000]

| Component | % by wt. landfilled[a] | Recycling Eff. (% generated)[b] | Landfilled Mass (lb/yr)[c] | Generated Mass (lb/yr)[d,e] | % Composition of Generated Waste[f] |
|---|---|---|---|---|---|
| Food | 12 | 0 | 14,400,000 | 14,400,000 | 9.6 |
| Paper | 40 | 30 | 48,000,000 | 68,571,429 | 45.7 |
| Plastic | 8 | 15 | 9,600,000 | 11,294,118 | 7.5 |
| Glass | 7 | 10 | 8,400,000 | 9,333,333 | 6.2 |
| Metal | 15 | 8 | 18,000,000 | 19,565,217 | 13 |
| Yard Waste | 0 | 100 | 0 | 5,235,903 | 3.5 |
| Other | 18 | 0 | 21,600,000 | 21,600,600 | 14.4 |

Example Calculations:

[a] Given

[b] Given

[c] For food, landfill mass: $\frac{12}{100} \times 120{,}000{,}000 = 14{,}400{,}000\ lb/yr$

[d] For paper, generated mass: $\frac{48{,}000{,}000}{1-0.3} = 68{,}571{,}429$

[e] Generated mass of yard waste = total waste generated – the generated mass of all other components: Generated Yard Waste = 150,000,000 – 144,764,097 = 5,235,903 lb/yr

[f] For paper, % Composition: $\frac{68{,}571{,}429}{150{,}000{,}000} \times 100 = 45.7\%$

Part B:

| Component | Landfilled Mass (lb/yr)[a] | Waste Density ($lb/yd^3$)[b] | Landfilled Volume ($yd^3/yr$)[c] |
|---|---|---|---|
| Food | 14,400,000 | 490 | 29,388 |
| Paper | 48,000,000 | 150 | 320,000 |
| Plastic | 9,600,000 | 110 | 87,273 |
| Glass | 8,400,000 | 330 | 25,455 |
| Metal | 18,000,000 | 540 | 33,333 |
| Yard Waste | 0 | 170 | 0 |
| Other | 21,600,000 | 810 | 26,667 |

522,115 $yd^3/yr$ (Total volume landfilled each year)[d]
10,442,301 volume in LF ($yd^3$) after 20 years[e]

**Answer:** 1.74 = CR[f]

Example Calculations:
a Given
b Take from tables provided
c For Food, landfilled volume: $\frac{14{,}400{,}000\ lb/yr}{490\ lb/yd^3} = 29{,}388\ yd^3/yr$
d Volume placed in the landfill each year is a summation of all volumes
e Total volume placed in a landfill after 20 years: $522{,}155 \frac{yd^3}{yr} * 20yr = 10{,}442{,}301\ yd^3$
f CR: $\frac{10{,}442{,}301\ yd^3}{6{,}000{,}000\ yd^3} = 1.74$

Problem 4:

Assume 100 lbs. of waste landfilled and calculate specific energy content of landfilled waste

| Component | Composition of landfilled waste (% wt.)[a] | Landfilled Mass (lb)[b] | Energy Content, BTU/lb wet waste[c] | Energy (BTU)[d] |
|---|---|---|---|---|
| Food | 15 | 15 | 1,797 | 26,955 |
| Mixed Paper | 30 | 30 | 6,799 | 208,970 |
| Glass | 7 | 7 | 84 | 588 |
| Plastic | 5 | 5 | 14,101 | 70,505 |
| Metals | 3 | 3 | 301 | 903 |
| Textiles | 7 | 7 | 7,960 | 55,720 |
| Wood | 8 | 8 | 6,640 | 53,120 |
| Yard Waste | 25 | 25 | 2,601 | 65,025 |

[e]**Total Energy** = 476,786 BTU
[f]**Specific Energy Content** = 4,768 BTU/lb waste landfilled

<u>Example Calculations:</u>

[a] Given

[b] For food, landfilled mass: $\frac{15}{100} \times 100 = 15\ lb$

[c] Given

[d] For food, BTU: $15\ lb\ \times 1797\ BTU/lb\ waste = 26955\ BTU$

[e] Summation of all individual BTU values

[f] Specific energy content = $\frac{476{,}786}{100} = 4{,}768 \frac{BTU}{lb\ waste}$

Determine total mass generated of each constituent and the specific energy content of the generated waste

| Component | Individual Recycling Eff. (%, generated waste)[a] | Generated Mass (lb)[b] | Energy Content (BTU/lb)[c] | Energy (BTU)[d] |
|---|---|---|---|---|
| Food | 0 | 15 | 1,797 | 26,955 |
| Mixed Paper | 70 | 100 | 6,799 | 679,900 |
| Glass | 40 | 12 | 84 | 980 |
| Plastic | 50 | 10 | 14,101 | 141,010 |
| Metals | 10 | 3 | 301 | 1,003 |
| Textiles | 0 | 7 | 7,960 | 55,720 |
| Yard Waste | 60 | 63 | 2,601 | 162,563 |
| Wood | 0 | 8 | 6,640 | 53,120 |

[e]**Total Energy** = 1,121,251 BTU
[f]**Specific Energy Content** = 5,155 BTU/lb waste generated

Example Calculations:

[a] Given

[b] For paper, generated mass: $\frac{30lb}{1-0.7} = 100\ lb$

[c] Given

[d] for food, BTU: $15\ lb\ \times 1797\ \ BTU/lb\ waste = 26{,}955\ BTU$

[e] Summation of all individual BTU values

[f] Specific energy content: $\frac{1{,}121{,}251\ BTU}{217.5\ lb} = 5{,}155\ \ BTU/lb\ waste$

[g]**Energy Reduction:** 7.51

[g] Energy Reduction =

$$\frac{(Specific\ Energy\ Content\ of\ generated\ waste)-(Specific\ Energy\ Content\ of\ landfilled\ waste)}{(Specific\ Energy\ Content\ of\ generated\ waste)}$$

## III. Physical Properties of Municipal Solid Waste

Problem 1:

1. Assume 100 lb of wet waste
2. Obtain typical moisture content values
3. Calculate the wet and dry weights of each component

| Waste Component | Composition (%, wt.) | MC (%, wet wt.) | Wet Weight (lb)[a] | Dry Weight (lb)[b] |
|---|---|---|---|---|
| Paper | 50 | 6 | 50 | 47 |
| Glass | 20 | 2 | 20 | 19.6 |
| Food | 20 | 70 | 20 | 6 |
| Yard Waste | 10 | 60 | 10 | 4 |
| | | | | |
| | **Total Weights (lb)**[c] | = | 100 | 76.6 |

[d]**Weight of water** (lb) = 23.4 lb
**Total Weight** = 100 lb

[e]**MC(%)** = 23.4

Example Calculations:
[a] For paper, Wet Weight: $100\ lb\ \times \frac{50}{100} = 50\ lb$
[b] For paper, Dry Weight: $50\ lb\ \times 0.94 = 47\ lb$
[c] Summation of the wet and dry weights
[d] Weight of water: $100\ lb - 76.6\ lb = 23.4\ lb$
[e] MC = $\frac{23.4\ lb}{100\ lb} = 23.4\ \%$

## IV. Chemical Properties of Municipal Solid Waste

**1.**

*Glossary:*

| Term | Definition |
|---|---|
| Proximate analysis | Approximate sample composition by determining: ash, moisture, fixed carbon, volatile matter |
| Ultimate analysis | Quantitative analysis of elements in a sample, usually C, H, O, N, S, and ash |
| HHV | Higher heating value: gross calorific value (assumes water is in the liquid phase following combustion) |
| LHV | Lower heating value: net calorific value (assumes water is in the vapor state following combustion) |

**2.** Solution is shown below, note that all example calculations are shown in the powerpoint file.

| Component | Wet Weight, g | % MC |
|---|---|---|
| Yard Wastes | 100 | 40 |

| Component | C | H | O | N | S | Ash |
|---|---|---|---|---|---|---|
| Yard Waste | 47.8 | 6 | 38 | 3.4 | 0.3 | 4.5 |

Mass of each element (g):

| C | H | O | N | S | Ash |
|---|---|---|---|---|---|
| 28.68 | 3.6 | 22.8 | 2.04 | .018 | 2.7 |

Weight of H and O:

H: 4.4 g H – (wt of moist/MW $H_2O$)*2

O: 35.6 g O – (wt of moist/MW $H_2O$)*16

| Element | g w/o Water | g with Water |
|---|---|---|
| C | 28.68 | 28.68 |
| H | 3.6 | 8.04 |
| O | 22.8 | 58.36 |
| N | 2.04 | 2.04 |
| S | 0.18 | 0.18 |
| Ash | 2.7 | 2.7 |

| Element | Atomic Wt (g/mole) | Moles, w/o Water | Moles, with Water |
|---|---|---|---|
| C | 12.01 | 2.388 | 2.388 |
| H | 1.01 | 3.564 | 7.965 |
| O | 16 | 1.425 | 3.647 |
| N | 14.01 | 0.146 | 0.146 |
| S | 32.07 | 0.006 | 0.006 |

| | N=1 | | S=1 | |
|---|---|---|---|---|
| Element | Mole Ratio w/o Water | Mole Ratio w/ Water | Mole Ratio w/o water | Mole Ratio w/ Water |
| C | 16.4 | 16.4 | 425.5 | 425.5 |
| H | 24.5 | 54.7 | 635 | 1419.1 |
| O | 9.8 | 25 | 253.9 | 649.8 |
| N | 1 | 1 | 25.9 | 25.9 |
| S | 0 | 0 | 1 | 1 |

Normalized to N:
With Water: $C_{16}H_{55}O_{25}N_1$
Without Water: $C_{16}H_{25}O_{10}N_1$

Normalized to S:
With Water: $C_{426}H_{1419}O_{650}H_{26}S_1$
$C_{426}H_{635}O_{254}N_{26}S$

**Problem 4:**

| Table 1. Waste Composition | | |
|---|---|---|
| Component | Wet Weight, g | % MC |
| Food Waste | 50 | 70 |
| Paper | 50 | 6 |

| Table 2. Chemical Composition of Waste Components | | | | | | |
|---|---|---|---|---|---|---|
| Component | C | H | O | N | S | Ash |
| Food Waste | 48 | 6.4 | 37.6 | 2.6 | 0.4 | 5 |
| Paper | 42.5 | 6 | 44 | 0.3 | 0.2 | 6 |

**Solution:**

Step 1: Calculate the weight of each element

| Component | Wet Weight, g | % MC | Dry Weight, g | C | H | O | N | S | Ash |
|---|---|---|---|---|---|---|---|---|---|
| Food Waste | 50 | 70 | 15 | 7.2 | 0.96 | 5.64 | 0.39 | 0.06 | 0.75 |
| Paper | 50 | 6 | 47 | 20.45 | 2.82 | 20.68 | 0.14 | 0.09 | 2.82 |
| TOTALS | 100 | | 62 | 27.65 | 3.78 | 26.32 | 0.53 | 0.15 | 3.57 |

Step 2: Calculate the weight of H and O in water

a) How much water is in this waste
   i. 38 g (wet waste – dry waste)
b) Calculate the weight of H and O in the waste
   H: 4.2 g H – (Wt of moist/MW of $H_2O$) x 2
   O: 33.8 g O – (Wt of moist/MW of $H_2O$) x 16

Step 3: Add the H and O to the composition found in above table

| Element | g w/o Water | g with Water |
|---|---|---|
| C | 27.65 | 27.65 |
| H | 3.78 | 8 |
| O | 26.32 | 60.10 |
| N | 0.53 | 0.53 |
| S | 0.15 | 0.15 |
| Ash | 3.57 | 3.57 |

Step 4: Determine molar composition of the elements. Ignore ash

| Element | Atomic Wt. (g/mole) | Moles, w/o Water | Moles. With Water |
|---|---|---|---|
| C | 12.01 | 2.302 | 2.302 |
| H | 1.01 | 3.743 | 7.923 |
| O | 16 | 1.645 | 3.756 |
| N | 14.01 | 0.038 | 0.038 |
| S | 32.07 | 0.005 | 0.005 |

Step 5: Normalize mole ratios

| | N=1 | | S=1 | |
|---|---|---|---|---|
| Element | Mole Ratio w/o Water | Mole Ratio with Water | Mole Ratio w/o Water | Mole Ratio with Water |
| C | 60.7 | 60.7 | 479.3 | 479.3 |
| H | 98.7 | 209.0 | 779.4 | 1649.9 |
| O | 43.4 | 99.1 | 342.6 | 782.2 |
| N | 1 | 1 | 7.9 | 7.9 |
| S | 0.1 | 0.1 | 1 | 1 |

**Chemical Formula:** $C_{480}H_{1650}O_{782}N_8S$

**Problem 5:**

Step 1: Find the dry weight of the waste (Follow procedures describes previously)

| Component | Wet Weight, lb | % MC | Dry Weight, lb |
|---|---|---|---|
| Food Waste | 8 | 70 | 2.4 |
| Paper | 28 | 6.1 | 263 |
| Cardboard | 8 | 5 | 7.6 |
| Plastics | 9 | 4.4 | 8.6 |
| Wood | 3 | 60 | 1.2 |
| Glass | 8 | 2.5 | 7.8 |
| Metals | 11.4 | 1.8 | 11.2 |

Step 2: Determine the energy content of each waste component
(dry solid waste weight x BTU)

| Component | Dry Weight, lb | Heat Value (BTU/lb dry waste) | BTU |
|---|---|---|---|
| Food Waste | 2.4 | 2,000 | 4,800 |
| Paper | 26.3 | 7,200 | 189,302 |
| Cardboard | 7.6 | 7,000 | 53,200 |
| Plastics | 8.6 | 14,000 | 120,456 |
| Wood | 1.2 | 8,000 | 9,600 |
| Glass | 7.8 | 60 | 468 |
| Metals | 11.2 | 300 | 3,358 |

Step 3: Calculate Specific BTU content of waste (BTU/lb)

$Total\ Energy\ (BTU)\ \div Total\ Waste\ (lb)$ = 5055.5 BTU/lb