Feed Conditioning — Energy

INTRODUCTION

The first law of thermodynamics states that energy can neither be created nor destroyed. Thus, energy that flows into a system must be fully accounted for either as energy stored within the system or energy that flows out of the system. In a composting process the major energy input is the organic molecules of the feed substrates. As these molecules are broken down by biological activity, energy is either transformed into new organic molecules within the microorganisms or is released as heat to the surroundings. Thus, it is energy release from organic decomposition that drives the composting process, causes temperature elevation and produces the drying that is so desirable with wet substrates. Indeed, it is the opportunity to capture a portion of this energy that causes microbes to decompose the organics in the first place.

This chapter examines the material and energy balances that govern the composting process and the feed conditioning necessary to provide sufficient energy to drive the process. The latter is termed "energy" conditioning. This chapter will show how composting can be divided into distinct thermodynamic regions: one in which sufficient energy is available for both composting and evaporative drying and another in which energy is sufficient only for composting with limited drying. It is essential that the feed substrates contain sufficient energy to accomplish the thermodynamic objectives of the process.

A simplified approach to material and energy balances is presented in this chapter. Closed form analytical solutions can be developed based on certain simplifying assumptions. These solutions can then be used to determine whether the feed mixture is properly conditioned from an energy standpoint. More detailed energy balances are pursued in Chapters 11 through 14.

HEAT AND MATERIAL BALANCES

Heat liberated from the decomposition of organics increases the temperature of solids, water, and air in the composting mixture. The released energy also drives the evaporation of

water, which is carried from the process in the exhaust gases. Because the compost is at a higher temperature than the surroundings, heat losses will occur from exposed surfaces of the compost. These losses are mitigated to some extent by the insulating effect of the compost, which limits conduction of heat. Losses will also occur as windrows or piles are mechanically turned. Under equilibrium conditions, the process temperature will rise to a point where energy inputs are balanced by outputs. However, maximum composting temperatures are generally limited to about 75 to 85°C because rates of biological activity become seriously reduced by thermal inactivation at such temperatures. The highest temperatures observed by this author are 88 to 90°C reported at the circular, agitated bed system in Plattsburgh, New York.

A schematic diagram of the composting process showing the thermodynamic system boundary and major process inputs and outputs is presented in Figure 8.1. Major inputs are substrate, other amendments, and process air, and its associated water vapor. Major outputs are the compost product, dry exhaust gases, and exit water vapor. The heat inputs and outputs associated with these materials are included in the analysis. Heat loss to the surroundings is not included, but it is usually a small fraction of the other heat outputs. Note also that compost recycle and bulking agent recycle are not shown. These material flows are internal to the system boundary and, therefore, do not affect the overall system balance. They are important to the balances on internal stages within the system boundary and are discussed further in Chapter 11.

Some new mass terms are introduced in this section. The terms BVS, NBVS, ASH, and WAT were defined in Chapter 6. Additional mass and energy terms are defined as follows (use of these terms is presented in the following examples):

Mass Terms
NBVSO   =   nonbiodegradable volatile solids in the compost product
ASHO   =   ash component in the compost product
WATSO   =   water component in the compost product
DAIRI   =   dry air input to the process
WATVI   =   water vapor associated with the air input
WATP   =   water produced during organic decomposition
DGASO   =   dry gas output from the process
WATVO   =   water vapor associated with the gas output

Energy Terms
HSI   =   sensible heat in the substrate solids
HWI   =   sensible heat in the water component of the substrate
HDAIRI   =   sensible heat in the input dry air
HSWVI   =   sensible heat in the water vapor associated with the input air
HORG   =   heat release by biological oxidation of the substrate
HTOTI   =   total input energy
HSO   =   sensible heat in the output product solids
HWO   =   sensible heat in the output water contained in the compost product
HDGASO   =   sensible heat in the output dry gases
HSWVO   =   sensible heat in the water vapor associated with the output gases
HLWVO   =   latent heat difference between the output water vapor and the input water vapor
HTOTO   =   total output energy
CPWAT   =   specific heat of water, taken as 1.00 cal/g-°C or Btu/lb-°F
CPSOL   =   specific heat of solids, taken as 0.25 cal/g-°C or Btu/lb-°F
CPGAS   =   specific heat of dry gases, taken as 0.24 cal/g-°C or Btu/lb-°F
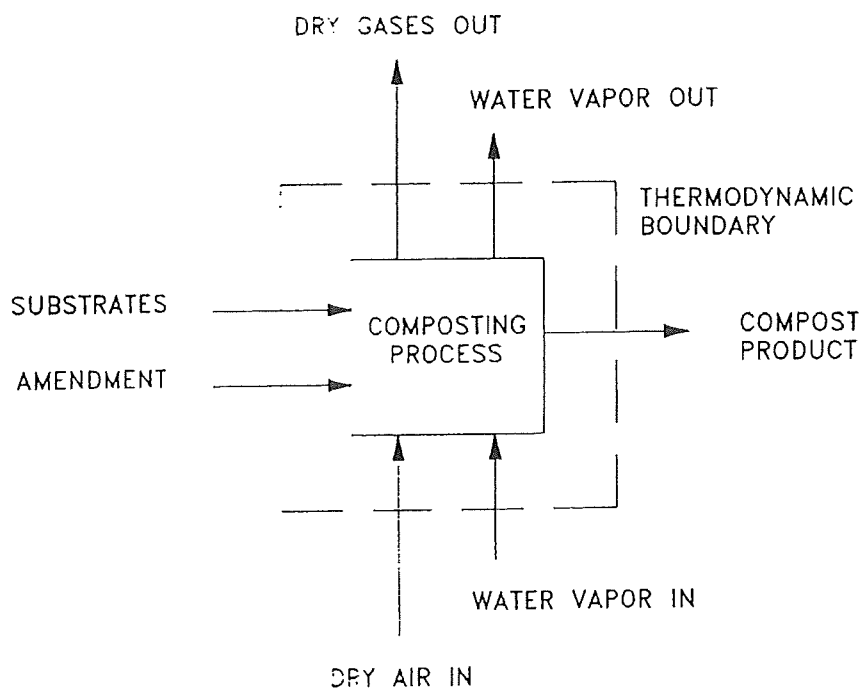
Figure 8.1. Thermodynamic system boundary and major material inputs and outputs to the composting process.

CPWATV = specific heat of water vapor, taken as 0.44 cal/g-°C or Btu/lb-°F

H_s = higher heat of combustion of the substrate, cal/g or Btu/lb of organics oxidized

H_a = higher heat of combustion of the amendment, cal/g or Btu/lb of organics oxidized

Composting of Wet Substrates

With wet substrates it is usually desirable to evaporate water during composting to produce a relatively dry product. The evaporative burden with wet substrates is considerably greater than with dry substrates. Therefore, the energy available from wet substrates is very critical because of the large energy burden placed on the system to support evaporation. The mass and energy balances for composting with drying are explored in the following examples.

Example 8.1

A wet substrate at 20% TS is to be composted. Compost recycle is used for conditioning with no other amendment or bulking agent added. The substrate is 80% VS ($V_s = 0.80$) with an estimated degradability of 60% ($k_s = 0.60$) and a composition of $C_{17}H_{29}O_3N$. A 60% TS content is desired in the compost product. Inlet air is 20°C and 75% relative humidity. The compost process will operate at 55°C. Assume the process gases are exhausted at 55°C saturated. Develop a system mass balance for these conditions based on a substrate feed rate of 5 kg/day (1 kg/day of substrate solids).

Solution

1. Using Equations 6.23 to 6.26 the components of the feed substrate are

$$
\begin{array}{lll}
\text{BVS} & = & (0.60)(0.80)(0.20)(5) & = & 0.480 \text{ kg/day} \\
\text{NBVS} & = & (1 - 0.60)(0.80)(0.20)(5) & = & 0.320 \\
\text{ASH} & = & (1 - 0.80)(0.20)(5) & = & 0.200 \\
\text{WAT} & = & 5 - (0.20)(5) & = & \underline{4.000} \\
\text{Substrate feed} & & & = & 5.000 \text{ kg/day}
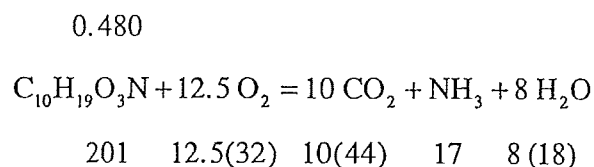\end{array}
$$

2. The weight of compost product can be determined by assuming that all BVS are lost during the composting process and that the NBVS and ASH fractions are conservative. Therefore,

$$
\begin{array}{lllll}
\text{NBVSO} & = & \text{NBVS} & = & 0.320 \text{ kg/day} \\
\text{ASHO} & = & \text{ASH} & = & \underline{0.200} \\
\text{Product solids} & & & = & 0.520 \text{ kg/day}
\end{array}
$$

The product solids are assumed to be 60% TS. The water component is

$$
\text{WATSO} = (0.520 / 0.60) - 0.520 = 0.347 \text{ kg} / \text{day}
$$

3. Water produced during composting WATP can be determined from the chemical formula for the substrate organics and assuming that all BVS are decomposed:

$$
0.480
$$

$$
C_{10}H_{19}O_3N + 12.5 \, O_2 = 10 \, CO_2 + NH_3 + 8 \, H_2O
$$

$$
201 \quad 12.5(32) \quad 10(44) \quad 17 \quad 8 \, (18)
$$

$$
\text{WATP} = 8(18)(0.480) / 201 = 0.344 \text{ kg} / \text{day}
$$

4. A mass balance on water gives

$$
\text{water in} + \text{water produced} = \text{water out}
$$
$$
\text{WAT} + \text{WATVI} + \text{WATP} = \text{WATVO} + \text{WATSO}
$$

Rearranging:

$$
\text{WATVO} - \text{WATVI} = \text{WAT} + \text{WATP} - \text{WATSO}
$$
$$
\text{WATVO} - \text{WATVI} = 4.000 + 0.344 - 0.347 = 3.997 \text{ kg} / \text{day}
$$

5. Using Equations 7.8 to 7.10 as shown in Example 7-4, the inlet and outlet gases have the following specific humidities:

$$
\text{inlet air} = 0.0113 \text{ g water/g dry air}
$$

$$
\text{outlet gas} = 0.1147 \text{ g water/g dry gas}
$$

6. Air required for moisture removal can be determined as follows. A water balance on the inlet and outlet gases gives the following equations:

$$WATVO = DGASO\,(0.1147)$$

$$WATVI = DAIRI\,(0.0113)$$

$$DGASO(0.1147) - DAIRI(0.0113) = 3.997$$

The quantity of dry exit gas DGASO will equal the inlet air, less oxygen consumed, plus the carbon dioxide and ammonia formed:

$$DGASO = DAIRI - \frac{0.480(12.5)(32)}{201} + \frac{0.480(10)(44)}{201} + \frac{0.480(17)}{201}$$

Solving the above simultaneous equations:

$$DAIRI = 38.501 \text{ kg/day}$$
$$DGASO = 38.638 \text{ kg/day}$$

7. The water vapor inputs and outputs are determined as

$$WATVI = 38.501(0.0113) = 0.435 \text{ kg/day}$$
$$WATVO = 38.638(0.1147) = 4.432 \text{ kg/day}$$

8. Check the total mass balance as follows:

In		Out	
BVS	0.480	NBVSO	0.320
NBVS	0.320	ASHO	0.200
ASH	0.200	WATSO	0.347
WAT	4.000	WATVO	4.432
WATVI	0.435	DGASO	38.638
DAIRI	38.501		
Total	43.936	Total	43.937

The total mass balance checks within the limits of roundoff errors. The water balance can be checked as follows:

In		Out	
WAT	4.000	WATSO	0.347
WATVI	0.435	WATVO	4.432
WATP	0.344		
Total	4.779	Total	4.779

The mass balance for the conditions of Example 8.1 is presented in Figure 8.2. Sufficient water is removed to produce a relatively dry compost product. Therefore, the conditions of Figure 8.2 can be described as "composting with drying". The question that now arises is whether sufficient energy is supplied by the feed substrate to accomplish both the composting and drying shown in Figure 8.2. If the substrate is "energy poor" then the conditions of Figure

DGASO   38.638

WATVO   4.432

SUBSTRATE

BVS	0.480
NBVS	0.320
ASH	0.200
WAT	4.000

	5.000

COMPOSTING PROCESS

T = 55 C

PRODUCT

NBVSO	0.320
ASHO	0.200
WATSO	0.347

	0.867

WATVI   0.435

DAIRI   38.501
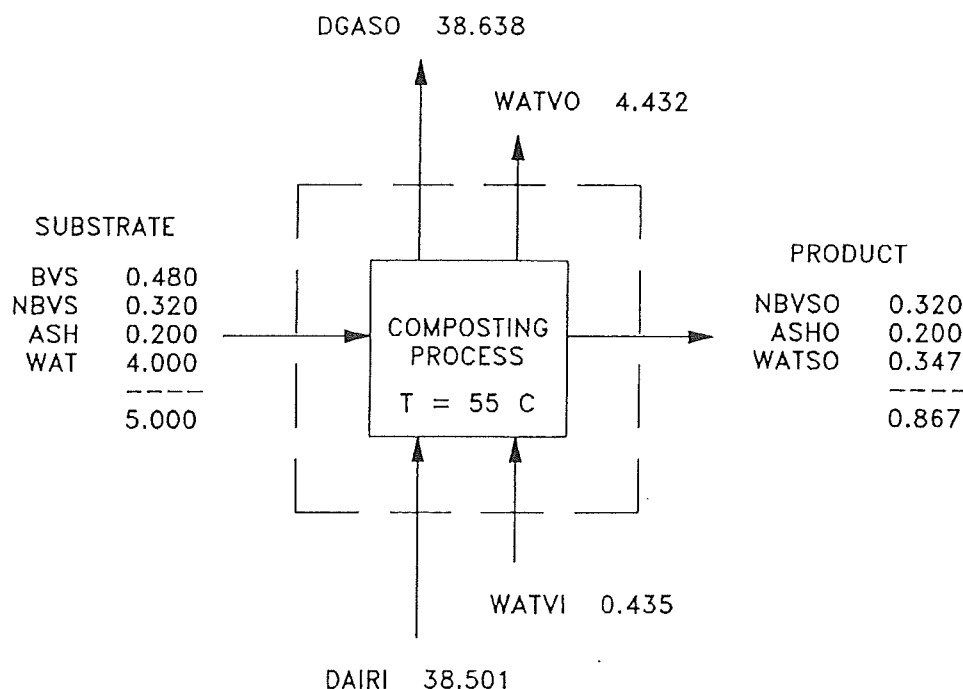
Figure 8.2.   Mass balance for the conditions of Example 8.1. The case is for a wet substrate with significant demands for drying. All units are kg/day and the balance is based on 1 kg/day of substrate solids.

8.2 may not be achievable. If this were the case and if the operator maintained the air supply as shown in Figure 8.2, process temperatures would fall. This reduces the evaporative heat loss, and the system will rebalance itself but at a lower process temperature. Alternatively, the operator could reduce the air supply to reduce the evaporative and other heat losses in the exhaust gas. Process temperatures could continue to be maintained, but drying would be limited. This illustrates the importance of knowing whether the feed substrate is "energy rich" or "energy poor" relative to the energy demands on the process.

The energy balance corresponding to Figure 8.2 is developed in the following example. Energy terms must be related to a datum or reference point for measurement. For convenience, a reference temperature TREF of 0°C (32°F) is used throughout this text. Further discussion of the reference datum and the assumed pathways for heat release is presented in Chapter 11.

Example 8.2.

Develop the energy balance for the conditions of Example 8.1. Assume substrate and air are input at 20°C and compost product and exhaust gases exit at 55°C.

Solution

1. The input energy terms HSI, HWI, HDAIRI, and HSWVI are determined using the form of Equation 3.8 as follows:

$$HSI = 1.0(0.25)(20 - 0) = 5.0 \text{ kcal/day}$$
$$HWI = 4.0(1.00)(20 - 0) = 80.0$$
$$HDAIRI = 38.501(0.24)(20 - 0) = 184.8$$

$$HSWVI = 0.435(0.44)(20 - 0) = 3.8$$

The heat release during composting is determined by assuming that all BVS are decomposed with a unit heat release, H_s, of 5550 cal/g BVS:

$$HORG = 0.480(5550) \qquad = \underline{2664.0}$$
$$HTOTI \qquad\qquad\qquad = 2937.6 \text{ kcal/day}$$

2. The output energy terms HSO, HWO, and HDGASO are determined as follows:

$$HSO = 0.520(0.25)(55 - 0) = 7.2 \text{ kcal/day}$$
$$HWO = 0.347(1.00)(55 - 0) = 19.1$$
$$HDGASO = 38.638(0.24)(55 - 0) = 510.0$$

Referring back to Example 3.1, a path must be defined to determine the sensible and latent heats in the exhaust water vapor. A convenient path is to assume that input water vapor and liquid water, which is evaporated, are first heated to the composting temperature (55°C in this case) and then the water is evaporated at the composting temperature. Sensible heat demand for this pathway is determined as

$$HSWVO = 0.435(0.44)(55–0)+(4.432–0.435)(1.00)(55–0) = 230.4$$
$$HSWVO \qquad\qquad\qquad\qquad\qquad\qquad = 230.4$$

The latent heat of vaporization at 55°C is determined from steam tables to be 565.7 cal/g. The latent heat of the exhaust water vapor is

$$HLWVO = (4.432–0.435)565.7 = \underline{2261.1}$$
$$HTOTO \qquad\qquad\qquad\qquad = 3027.8 \text{ kcal/day}$$

The total of energy output terms HTOTO is slightly greater than the total of input energy terms (HTOTI) in Example 8.2. This means that the mass balance in Figure 8.2 must be adjusted slightly to reduce HTOTO to balance that supplied by the substrate. As a practical matter, the air input could be reduced slightly to reduce the evaporative burden. This in turn would slightly reduce the output solids content. The solution point is achieved when both the mass and energy balances are closed simultaneously. Obviously, a trial and error approach is required to simultaneously close both the mass and energy balances. The reader should not despair at the prospect of doing trial and error solutions. The computer programs presented in Chapter 11 can manage such tedious calculations for the reader.

As an alternative to producing a wetter product, the substrate in Example 8.1 could be "energy conditioned" to increase the energy supply and close the balance. The most common approach to energy conditioning is to add other degradable, relatively dry substrates to increase the energy resources without significantly adding to the water burden. This approach to closing the energy balance is discussed later in this chapter.

Several lessons are apparent from the results of Examples 8.1 and 8.2. First, air supply is the dominant term in the mass balance, accounting for nearly 88% of the total mass of input materials. Second, the heat release from organic oxidation (HORG) is the major energy input term. Sensible heats contributed by input solids, water, and air are minor by comparison. Third, the latent heat of vaporization (HLWVO) is the dominant energy output term. With the

wet substrate of Examples 8.1 and 8.2, latent heat accounts for about 75% of the total output energy. Sensible heat in the output dry gases (HDGASO) is the next largest term, accounting for about 17% of the total. Together HLWVO and HDGASO account for over 90% of the total energy demand.

Composting of Dry Substrates

The requirement for moisture removal is not as severe with dry substrates as it is with wet substrates. The reduced demand for water evaporation means that the air supply can be reduced toward the stoichiometric demand. Heat removal will be less in this case and very high process temperatures may result. The mass and energy balances associated with the composting of dry substrates are explored in the following examples.

Example 8.3

The company producing the wet substrate of Example 8.1 is considering the installation of additional dewatering equipment to increase the solids content to 45%. Develop the new mass balance for this situation assuming all other conditions remain the same.

Solution

1. To maintain consistency with Example 8.1, again assume 1 kg of substrate solids. The total weight of feed substrate is then $1/0.45 = 2.222$ kg. Using Equations 6.23 to 6.26 the components of the feed substrate are

$$
\begin{array}{lll}
\text{BVS} & = & (0.60)(0.80)(0.45)(2.222) & = & 0.480 \text{ kg/day} \\
\text{NBVS} & = & (1 - 0.60)(0.80)(0.45)(2.222) & = & 0.320 \\
\text{ASH} & = & (1 - 0.80)(0.45)(2.222) & = & 0.200 \\
\text{WAT} & = & 2.222 - (0.45)(2.222) & = & 1.222 \\
\end{array}
$$

$$
\text{Substrate feed} \qquad = \quad 2.222 \text{ kg/day}
$$

2. The weight of compost product remains the same as in Example 8.1:

$$
\begin{array}{lll}
\text{NBVSO} & = & 0.320 \text{ kg/day} \\
\text{ASHO} & = & 0.200 \\
\text{WATSO} & = & 0.347 \\
\end{array}
$$

$$
\text{Compost product} \quad = \quad 0.520 \text{ kg/day}
$$

3. Assuming that all BVS decompose, the water produced during composting will remain the same as Example 8.1. Therefore, WATP = 0.344 kg/day.

4. The water balance becomes

$$
\begin{array}{lll}
\text{WATVO} - \text{WATVI} & = & \text{WAT} - \text{WATSO} + \text{WATP} \\
\text{WATVO} - \text{WATVI} & = & 1.222 + 0.344 - 0.347 = 1.219 \text{ kg/day} \\
\end{array}
$$

5. The inlet and outlet gases have the same specific humidities determined in Example 8.1. A water balance on the inlet and outlet gases gives the following equations:

$$WATVO = DGASO (0.1147)$$
$$WATVI = DAIRI (0.0113)$$

$$DGASO(0.1147) - DAIRI(0.0113) = 1.219$$

The quantity of dry exit gases (DGASO) will equal the inlet air, less oxygen consumed, plus the carbon dioxide and ammonia formed:

$$DGASO = DAIRI - \frac{0.480(12.5)(32)}{201} + \frac{0.480(10)(44)}{201} + \frac{0.480(17)}{201}$$

Solving the above simultaneous equations:

$$DAIRI = 11.634 \text{ kg/day}$$
$$DGASO = 11.771 \text{ kg/day}$$

6. The water vapor inputs and outputs are determined as

$$WATVI = 11.634(0.0113) = 0.131 \text{ kg/day}$$
$$WATVO = 11.771(0.1147) = 1.350 \text{ kg/day}$$

7. Check the total mass balance as follows:

In		Out	
BVS	0.480	NBVSO	0.320
NBVS	0.320	ASHO	0.200
ASH	0.200	WATSO	0.347
WAT	1.222	WATVO	1.350
WATVI	0.131	DGASO	11.771
DAIRI	11.634		
Total	13.987	Total	13.988

The water balance can be checked as follows:

In		Out	
WAT	1.222	WATSO	0.347
WATVI	0.131	WATVO	1.350
WATP	0.344		
Total	1.697	Total	1.697

7. The stoichiometric oxygen demand can be determined from the balanced oxidation reaction presented in Example 8.1:

$$\text{Oxygen demand} = 0.480(12.5)(32) / 201 = 0.955 \text{ kg } O_2 / \text{day}$$

The stoichiometric air demand is determined by recalling that air is 23.2% oxygen by weight:

$$\text{Air demand} = \frac{0.955}{0.232} = 4.116 \text{ kg air / day}$$
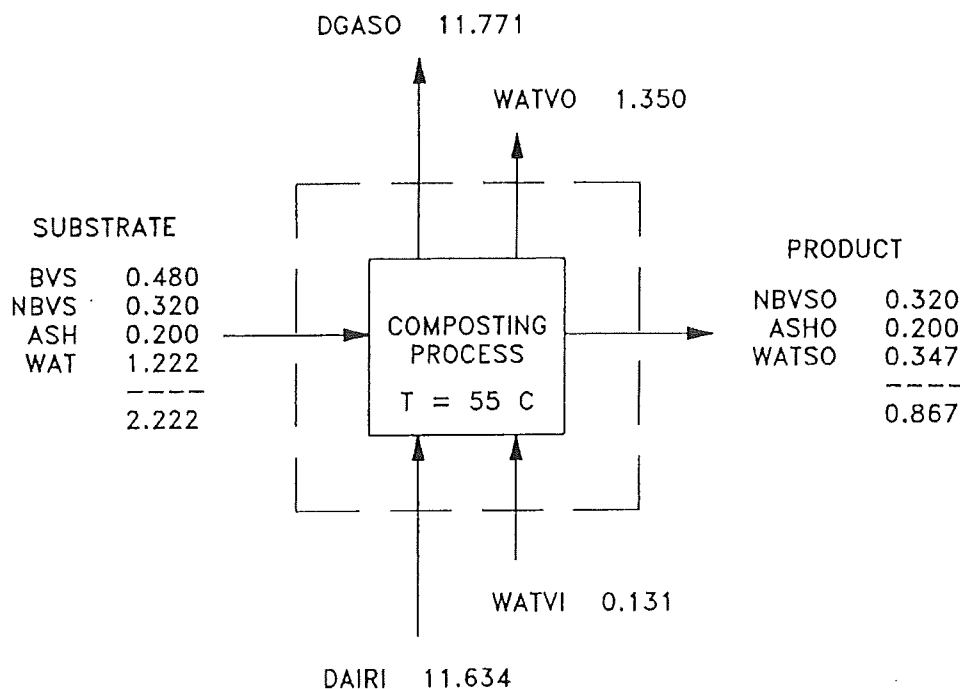
Figure 8.3.   Mass balance for the conditions of Example 8.3. The case is for a relatively dry substrate with limited demands for moisture removal. All units are kg/day and the balance is based on 1 kg/day of substrate solids.

8. Recall that the excess air ratio EAR is defined as the ratio of actual air supply to the stoichiometric demand. The EAR for this case is

$$EAR = 11.634 / 4.116 = 2.83$$

Even though the substrate in Example 8.3 is relatively dry, the air requirement for moisture removal is several times greater than the stoichiometric demand. However, the EAR of 2.83 is about as low as would normally be maintained in any composting system. The average oxygen content in the exhaust gas would be only ~13.6% with an EAR of 2.83. Further reducing the oxygen content would increase the possibility of oxygen rate limitations. Therefore, the mass balance presented in Example 8.3 should be reasonably representative of "composting with limited drying".

The mass balance for the conditions of Example 8.3 is presented in Figure 8.3. The demand for evaporative drying is greatly reduced compared to the wet substrate of Example 8.1. Nevertheless, air supply remains the dominant mass term accounting for over 83% of the total mass input. The energy balance for the conditions of Figure 8.3 is considered in Example 8.4.

Example 8.4

Develop the energy balance for the conditions of Example 8.3. Other conditions remain the same as for Example 8.2.

Solution

1. The input energy terms HSI, HWI, HDAIRI, and HSWVI are determined as

$$
\begin{aligned}
\text{HSI} &= 1.0(0.25)(20-0) &= 5.0 \ \text{kcal/day} \\
\text{HWI} &= 1.222(1.00)(20-0) &= 24.4 \\
\text{HDAIRI} &= 11.634(0.24)(20-0) &= 55.8 \\
\text{HSWVI} &= 0.131(0.44)(20-0) &= 1.2
\end{aligned}
$$

Heat release is the same as for Example 8.2

$$
\begin{aligned}
\text{HORG} &= 0.480(5550) &= 2664.0 \\
\text{HTOTI} & &= 2750.4 \ \text{kcal/day}
\end{aligned}
$$

2. The output energy terms are determined as follows:

$$
\begin{aligned}
\text{HSO} &= 0.520(0.25)(55-0) &= 7.2 \ \text{kcal/day} \\
\text{HWO} &= 0.347(1.00)(55-0) &= 19.1 \\
\text{HDGASO} &= 11.771(0.24)(55-0) &= 155.4 \\
\text{HSWVO} &= 0.131(0.44)(55-0) + \\
& \quad (1.350-0.131)(1.00)(55-0) &= 70.2 \\
\text{HLWVO} &= (1.350-0.131)565.7 &= 689.6 \\
\text{HTOTO} & &= 941.5 \ \text{kcal/day}
\end{aligned}
$$

The energy balance for the case of a relatively dry substrate differs markedly from that for a wet substrate. Total energy demand (HTOTO) is much less than that available from the substrate. No further energy conditioning is required for the substrate of Examples 8.3 and 8.4. Because heat release is so much greater than heat demand, changes in the conditions of Figure 8.3 would be necessary to reach a solution point where both the mass and energy balances are closed. Process temperatures are likely to exceed the assumed 55°C because so much additional heat is available. The higher process temperatures will cause an increase in the evaporative loss of water and result in a dryer product. The combination of high temperature and lower moisture content could impose kinetic limitations to the extent that the assumption of complete BVS loss is no longer valid. Methods to control the process to avoid such limitations and close both mass and energy balances are discussed in Chapters 11 to 14.

Several lessons are apparent from the results of Examples 8.3 and 8.4. First, air supply remains the dominant term in the mass balance even for relatively dry substrates. Second, the energy balance is not as critical as with wet substrates because the evaporative burden is greatly reduced. Third, despite the reduction in the evaporative burden the latent heat of vaporization (HLWVO) remains the dominant energy demand. With the relatively dry substrate of Examples 8.3 and 8.4, the latent heat accounts for ~73% of the total energy demand.

ENERGY FACTORS

If energy supply is less than demand, the feed mixture must be energy conditioned to remove the thermodynamic limitation. Several factors and rules of thumb were developed by Haug and Haug[1] and Haug[2] to judge the need for energy conditioning, but without the need to conduct mass and energy balances of the type presented in Examples 8.1 through 8.4.

The Water Ratio, W

The assumptions of Examples 8.1 and 8.2 are reasonably typical of conditions expected

with composting and drying of wet substrates. A rule of thumb termed the water ratio, W, can be developed from the results of Examples 8.1 and 8.2. W is defined as the ratio of water to degradable organics. Defining W on the basis of water content is a rational approach because evaporation represents most of the total energy demand. For the conditions of Example 8.1, produced water (WATP) nearly equals that in the compost product (WATSO). Therefore, water input with the substrate WAT (4.0 kg) is nearly equal to that evaporated. Substrate BVS was 0.48 kg. Using these values the W ratio is about 4.0/0.48 = 8.3.

Considering the assumptions involved, a W value of about 8 to 10 g H_2O/g BVS can be used to judge the thermodynamic characteristics of the composting process. Because water evaporation is the major energy use, and as long as moisture in the substrate is the major water input, the factor should apply equally to windrow, aerated pile, and reactor systems. If W < 8, sufficient energy should be available for temperature elevation and water evaporation. If W > 10, the substrate alone may not provide sufficient energy. Lower process temperatures or less drying can be expected.

To determine W for a particular substrate, consider the process diagram of Figure 6.7. The weight of water in feed substrate and amendments is given by

$$\text{weight water} = (X_s - S_s X_s) + (X_a - S_a X_a) \tag{8.1}$$

The quantity of degradable organics BVS in the mixture is given by

$$BVS = k_s V_s S_s X_s + k_a V_a S_a X_a \tag{8.2}$$

Combining Equations 8.1 and 8.2:

$$W = \frac{\text{weight of water}}{\text{weight degradable organics}}$$

$$W = \frac{(X_s - S_s X_s) + (X_a - S_a X_a)}{k_s V_s S_s X_s + k_a V_a S_a X_a} \tag{8.3}$$

The rationale for use of total infeed water in Equation 8.3, instead of the amount actually evaporated, is that most of the infeed water is evaporated with wet substrates and the calculations are thus simplified. It should be remembered that W is intended only as a tool or rule of thumb to judge the thermodynamic characteristics of the composting process. Thus, some compromise in technical accuracy is justified to give a tool that can be applied easily. W is not a substitute for a complete energy balance.

The Energy Ratio, E

One limitation with the W ratio is the assumption that all substrate organics have the same heat value. Of course, substrates can vary significantly in heat content depending on their composition. This limitation can be removed by including the heat content, H, in the analysis. Again referring to Examples 8.1 and 8.2, the heat released from the 0.48 Kg of BVS at 5550 kcal/kg is 2664 kcal. Dividing this value by the 4.0 Kg of substrate water gives a value of 666 cal/g H_2O. The latter is termed E or the energy ratio defined as follows:

$$E = \frac{\text{heat released}}{\text{weight of water}}$$

Substituting terms from Equations 8.1 and 8.2:

$$E = \frac{(k_s V_s S_s X_s)H_s + (k_a V_a S_a X_a)H_a}{(X_s - S_s X_s) + (X_a - S_a X_a)} \quad (8.4)$$

Considering the assumptions involved, an E ratio of about 700 cal/g water (1260 Btu/lb) can be used as a measure of the energy content of the substrate. If E is greater than 700 cal/g sufficient energy should be available for both composting and drying. If E is<600 cal/g, drying may have to be reduced to maintain process temperatures. Like its cousin the W ratio, the E ratio is a rule of thumb that compromises some technical accuracy to provide a usable tool.

Example 8.5

A municipal agency produces both raw and digested biosolids at 20% TS. The raw sludge is 80% VS with a 65% degradability. The digested sludge is 55% VS with 45% degradability. The heat value for both sludge types is 5550 cal/g VS. Estimate the W and E ratios for both sludges.

Solution

1. Assume 1 g of dry solids for each sludge type, equal to 1/0.2 = 5 g wet weight. W and E for the raw sludge are determined from Equations 8.3 and 8.4:

$$W = [5 - (0.20)(5)]/[0.65(0.80)(0.20)(5)]$$

$$W = 7.69 \qquad (W < 8)$$

$$E = [0.65(0.80)(0.20)(5)](5500)/[5 - (0.20)(5)]$$

$$E = 720 \text{ cal/g} \qquad (E > 700)$$

The raw sludge meets both rules of thumb.

2. W and E for the digested sludge are similarly calculated:

$$W = [5 - (0.20)(5)]/[0.45(0.55)(0.20)(5)]$$

$$W = 16.2 \qquad (W > 8)$$

$$E = [0.45(0.55)(0.20)(5)](5500)/[5 - (0.20)(5)]$$

$$E = 343 \text{ cal/g} \qquad (E < 700)$$

The digested sludge does not meet either of the rules of thumb.

3. These two sludge types are markedly different in their energy contents. The digested biosolids would require further energy conditioning to accomplish both composting and drying. The raw biosolids, however, should have sufficient energy for both composting and drying without supplemental energy amendments.

CONTROLLING THE ENERGY BALANCE

If a substrate or mixture of substrates does not contain sufficient energy to drive the composting process, further conditioning is required to control the energy balance. In such a case, the energy budget can be controlled by one or more of the following approaches: (1) limiting drying during composting, (2) reducing the substrate water content, and (3) adding supplemental energy amendments.

Control by Limiting Drying

One approach to controlling the energy balance is to reduce the evaporation of water and, thereby, reduce the total heat demand. This can be accomplished by controlling and reducing the air supply to limit evaporation. The problem with this approach is that reducing the drying potential removes one of the major advantages of composting, the production of a relatively dry product. With wet substrates the drying usually must be reduced to the point that the final product is still very wet. This can be seen by examining the digested sludge case in Example 8.5. The digested sludge solids contain about 1373 cal/g. Using 700 cal/g of water, about 1373/700 = 1.96 g water evaporation could be supported. The final product would contain about 4.0 g from the original substrate plus about 0.18 g produced water minus the 1.96 g evaporated. This gives about 2.22 g water in a final compost quantity of [1 − 0.45(0.55)(1)] = 0.75 gms. The solids content of the product would be about 0.75/(2.22 + 0.75) = 0.25 or ~25% TS to close the energy balance. With such a high moisture content, the final product would be unsuitable for reuse in most cases.

Control of the energy balance by limiting drying is a viable approach for wet substrates only if provision is made to adjust the final product moisture content by one or both of the following methods. First, moisture removal by air drying can be achieved in arid climates with open systems, such as the windrow process. In such cases, a dry product can sometimes be achieved, even though the starting sludge may not contain sufficient energy for complete moisture removal. Alternatively, heat drying could be used to dry the compost product. Second, a dry, stable structural amendment can be added to produce an acceptable final product. Some sawdusts meet these criteria, for example. While the amendment may add to the energy balance, it also serves to condition the final compost to an acceptable moisture content.

Improved Dewatering

A second approach to closing the energy balance is to reduce the water content of the substrate. With municipal and industrial sludges this means achieving higher cake solids from dewatering. This approach is examined in the following example.

Example 8.6

The municipal agency in Example 8.5 plans to install improved dewatering equipment for the digested biosolids. A 35% cake is expected. Determine the W and E ratios assuming that all other conditions remain the same.

Solution

1. Assuming 1 g of solids, the cake wet weight is $1/0.35 = 2.86$ g. The W and E ratios become

$$W = [2.86 - (0.35)(2.86)]/[0.45(0.55)(0.35)(2.86)]$$

$$W = 7.5 \qquad\qquad (W < 8)$$

$$E = [0.45(0.55)(0.35)(2.86)](5500)/[2.86 - (0.35)(2.86)]$$

$$E = 740 \text{ cal/g} \qquad\qquad (E > 700)$$

2. The 35% TS digested sludge cake satisfies the rules of thumb and should contain sufficient energy for both composting and drying.

With wet substrates such as municipal biosolids, maximizing cake solids from dewatering is one of the most effective approaches to controlling the energy balance. Dewatering and composting are integrally related. Success in sludge composting depends heavily on the ability to achieve dry cake solids. Both the designer and operator should consider dewatering as part of the feed conditioning process.

Product Recycle and the Energy Budget

The use of product recycle for structural conditioning was discussed in Chapter 6. Product recycle is a proven method of providing structural conditioning of wet substrates. However, recycle of compost product does not add new BVS to the system. Material recycle is an internal loop within the system boundary and therefore does not add to the system energy balance. Any BVS remaining in the recycle are contributed by the original substrate or amendment. Since the latter are already included in the balances presented in this chapter, including them again would cause a double accounting. Therefore, product recycle is useful for structural conditioning but not energy conditioning.

Amendment Addition

Case studies using amendment alone and amendment with product recycle for purposes of structural conditioning were presented in the bar diagrams of Figures 6.12 and 6.13. The use of amendment alone can provide effective structural conditioning, but at the cost of using considerable amounts of amendment. Product recycle can also provide effective structural conditioning, but it does not contribute new organics to the system. A compromise between

use of product recycle alone (potential energy problem) and use of amendment alone (quantity problem) is possible. If recycle is used for most of the structural conditioning, then smaller quantities of amendment can be added for control of the energy balance. In other words, amendment is added for energy conditioning and recycle added as necessary for further structural conditioning.

Equations for estimating the quantity of amendment required for energy conditioning can be developed based on certain simplifying assumptions. Based on the above examples, the latent heat of vaporization usually represents about 70 to 80% of the total energy demand. The system energy demand can be estimated with sufficient accuracy by multiplying the pounds of water evaporated by a factor termed H_e. The latter is an estimate of the system energy demand expressed as cal/g of water evaporated. H_e is typically in the range of 700 to 850 cal/g water evaporated (1260 to 1530 Btu/lb).

Referring to the process diagram of Figure 6.7, there are three unknowns in the problem: X_r, X_a, and X_m. Three equations are required for solution and can be developed from balances on water, solids, and energy across the system boundary in Figure 6.7.

Water balance

$$\text{water in} = (X_s - S_s X_s) + (X_a - S_a X_a)$$
$$\text{water out} = (X_p - S_p X_p) = X_p (1 - S_p)$$
$$\text{water evap} = \text{water in} - \text{water out}$$

$$\text{water evap} = (X_s - S_s X_s) + (X_a - S_a X_a) - X_p (1 - S_p) \tag{8.5}$$

Note that Equation 8.5 does not include the water of formation WATP, which is relatively small and neglected in this analysis.

Solids balance

$$\text{solids remaining} = \text{solids in} - \text{solids degraded}$$

$$S_p X_p = S_s X_s + S_a X_a - (k_s V_s S_s X_s) - (k_a V_a S_a X_a) \tag{8.6}$$

Heat balance

$$\text{heat in} = \text{heat out}$$

$$(k_s V_s S_s X_s) H_s + (k_a V_a S_a X_a) H_a = (\text{water evap})(H_e) \tag{8.7}$$

Substituting Equation 8.6 into 8.5 for X_p, substituting Equation 8.5 into 8.7, and rearranging gives the following equation for X_a:

$$X_a = \frac{H_e[(X_s - S_s X_s) - (S_s X_s - k_s V_s S_s X_s)(1/S_p - 1)] - H_s(k_s V_s S_s X_s)}{H_a(k_a V_a S_a) + H_e[(S_a/S_p - 1) - (k_a V_a)(S_a/S_p - S_a)]} \tag{8.8}$$

Once X_a is calculated from Equation 8.8, the mixture moisture content resulting from sludge and amendment alone can be determined as

$$S_m = (S_s X_s + S_a X_a) / (X_s + X_a) \tag{8.9}$$

Let SMMIN = the minimum acceptable mixture solids content, usually between about 0.35 and 0.45. Then,

if $S_m \geq$ SMMIN, then $X_r = 0$

if $S_m <$ SMMIN, then recycle must be added

The quantity of recycle to be added if $S_m <$ SMMIN is determined as

$$SMMIN = (S_s X_s + S_a X_a + S_r X_r) / (X_s + X_a + X_r)$$

solving for X_r:

$$X_r = \frac{SMMIN(X_s + X_a) - S_s X_s - S_a X_a}{(S_r - SMMIN)} \quad (\text{for } X_r > 0) \qquad (8.10)$$

Example 8.7

10 dtpd of the digested sludge cake in Example 8.5 is to be composted to produce a 60% TS product. The sludge will be conditioned with amendment and recycled product. Sawdust is the energy amendment and is to be added in sufficient quantity to close the energy balance. Recycled product will provide additional structural conditioning as necessary to reach a minimum mixture solids content of 40%. The sawdust is 70% TS, 95% VS, and 40% degradable. H_e is estimated at 1500 Btu/lb water evaporated. H_s is 10,000 Btu/lb of sludge organics and H_a 6500 Btu/lb of sawdust organics. Determine the required quantities of amendment and product recycle.

Solution

1. X_s is $10/0.20 = 50$ tpd.

2. X_a is determined from Equation 8.8 as

$$X_a = \frac{1500\{[50 - 0.20(50)] - [0.20(50) - 0.45(0.55)(0.20)(50)] \cdot [(1/0.60) - 1]\} - 10000[0.45(0.55)(0.20)(50)]}{6500[0.40(0.95)(0.70)] + 1500\{[(0.70/0.60) - 1] - [0.40(0.95)[(0.70/0.60) - 0.70]]\}}$$

$$X_a = 16.2 \text{ tpd}$$

3. Using Equation 8.9 the mixture solids content from the substrate and amendment is

$$S_m = \frac{0.20(50) + 0.70(16.2)}{50 + 16.2} = 0.322 = 32.2\% \text{ TS}$$

4. Because S_m is less than the desired SMMIN of 0.40 (40% TS) recycle of product is necessary to provide additional structural conditioning. The required X_r is determined from Equation 8.10:
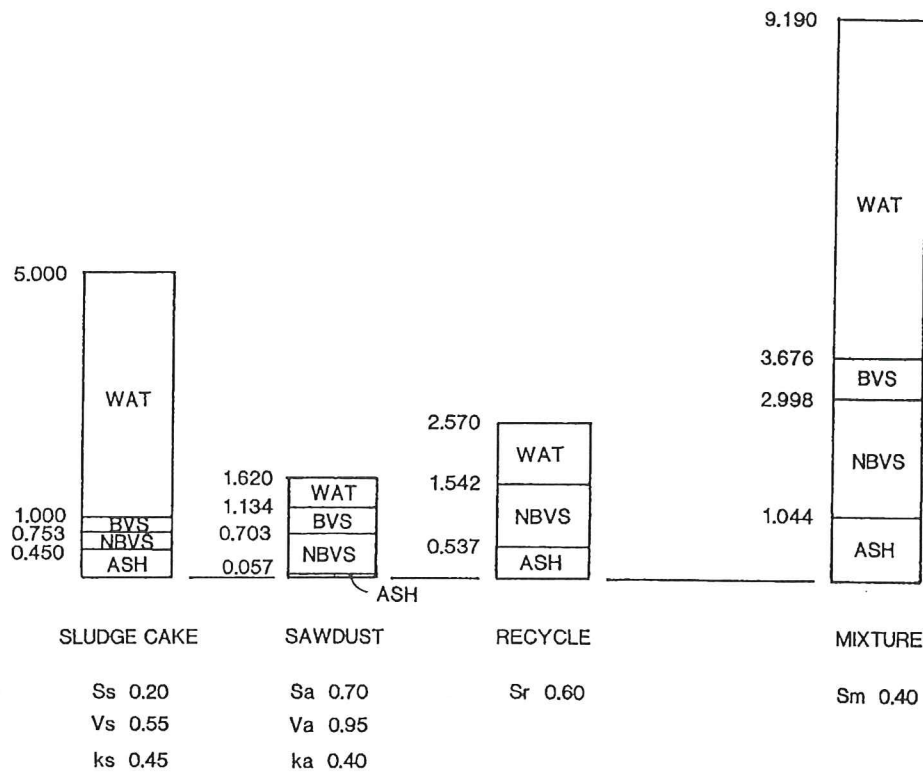
Figure 8.4.   Bar diagram of the substrate/amendment/recycle mixture for conditions of Example 8.7. The mixture is properly conditioned from both standpoints of energy and structure.

$$X_r = \frac{0.40(50 + 16.2) - 0.20(50) - 0.70(16.2)}{(0.60 - 0.40)}$$

$$X_r = 25.7 \text{ tpd}$$

5. A bar diagram showing the mixture and individual components is presented in Figure 8.4. The mixture is properly conditioned in terms of both structure and energy. The mixture should contain sufficient energy resources to accomplish the objective of composting with drying.

Use of amendment for energy conditioning and product recycle for additional structural conditioning represents an optimal approach to adjusting the composition of the infeed mixture.[3] Amendment use is reduced to the minimum required to satisfy the energy balance. Free air space is then adjusted as necessary using product recycle, which is available at no cost to the operator.

SUMMARY

Energy released by organic decomposition is the driving force for organic stabilization, temperature elevation, and moisture evaporation, all of which are desirable aspects of composting. Therefore, application of thermodynamic principles is a fundamental method for analyzing composting systems. Composting can be divided into two thermodynamic regions based on the energy and moisture contents of the substrate: one in which sufficient energy is available for both composting and drying and another in which energy is sufficient for

composting with only limited drying. "Energy" conditioning of the feed mixture is a key point of process control for the system designer and operator.

The energy balance with dry substrates differs uniquely from that for wet substrates. The added evaporative burden with wet substrates imposes additional energy demands that must be provided by the substrates. With wet substrates, particular attention must be paid to assure proper energy conditioning. With dry substrates, an excess of energy supply can result in high process temperatures and over drying, both of which must be corrected by plant operations.

Air supplied to the process and exhaust gases removed from the process are the dominant terms in the mass balance. This is true even with relatively dry substrates for which the air supply is reduced to an excess air ratio of only 2 to 3. Heat released from organic oxidation is the major energy input term. The sensible heat contributed by input solids, water, and air is minor by comparison. The latent heat of vaporization is the dominant output energy term, even with relatively dry substrates where the evaporative burden is reduced. The latent heat usually accounts for about 75% of the total output energy.

Two rules of thumb are presented to determine the requirements for energy conditioning without the need to conduct complete mass and energy balances. Each is based on the fact that the latent heat of vaporization is the major energy output. The water ratio, W, is defined as the ratio of substrate water to degradable organics. The energy ratio, E, is defined as the heat released per unit weight of substrate water. If $W < 8$ or $E > 700$ cal/g sufficient energy should be available for both composting and moisture evaporation. At $W > 10$ or $E < 600$ cal/g, composting temperatures can be maintained only if drying is limited by control of the air supply. Both W and E are rules of thumb that compromise some technical accuracy to provide a tool that is easy to use.

If a substrate or mixture of substrates does not contain sufficient energy to drive the composting process, further conditioning is required to control the energy balance. In such a case, the energy budget can be controlled by one or more of the following approaches: (1) limiting drying during composting by controlling and reducing the air supply, (2) reducing the substrate water content by improved dewatering, and (3) adding supplemental energy amendments. If the energy balance is controlled by reducing the air supply, provision must be made to either dry the final product or add moisture absorbing amendments.

Adding supplemental energy amendments is a favored approach to closing the energy balance. Use of degradable amendments for energy conditioning and product recycle for additional structural conditioning represents an optimal approach to adjusting the composition of the infeed mixture. Amendment use is reduced to the minimum required to satisfy the energy balance. Free air space can then be adjusted as necessary using product recycle, which is available at no cost to the operator.

With municipal biosolids, the cake solids from dewatering is the critical parameter that determines the thermodynamic region of operation. Using typical values for degradability, the W and E ratios should be in a range where energy is sufficient for both composting and drying, with cake solids above about 30 to 35% for digested biosolids and 20 to 25% for raw biosolids.

The dewatering of wet substrates such as biosolids is integrally related to the composting process. The two unit processes should not be viewed separately because success in composting depends heavily on the ability to achieve dry cake solids. The solids content produced during dewatering is probably the single most important variable in determining the successful composting of biosolids. Implementation of any composting system for biosolids cake should be coordinated with design of the dewatering process to obtain cake solids with sufficient energy to drive the composting process. If this cannot be accomplished by dewatering alone, the addition of supplemental energy amendments is the favored approach to "energy condition" the feed mixture.