CHAPTER

The composting process

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1. Introduction

Composting is the aerobic, or oxygen-requiring, decomposition of organic materials by microorganisms under controlled conditions. During composting, microorganisms use oxygen (O_2) while consuming organic matter present in the raw materials, commonly called feedstocks (Fig. 3.1). Active composting generates considerable heat while carbon dioxide (CO_2) and water vapor are released into the air. CO_2 (Fig. 3.2). Water losses can amount to more than half the weight of the original feedstocks. Composting thus reduces both the volume and mass of the feedstocks while transforming them into compost, a valuable soil conditioner.

The feedstocks provide the nutrients (e.g., carbon and nitrogen) and energy for the microorganisms. The microorganisms come with the feedstocks and from the surrounding environment, or may be added by recycling finished compost or with inoculants. The volume and mass of the finished compost can be one half to less than one quarter the starting volume.

Composting is most rapid when conditions that encourage the growth of the decomposer microorganisms are established and maintained (Table 3.1). The most important conditions include:

- Organic materials appropriately mixed and sized to provide the nutrients needed for microbial, activity, and growth, including a balanced supply of carbon and nitrogen (C:N ratio),
- Enough moisture to permit biological activity without hindering aeration,
- Oxygen at levels that support aerobic decomposition, and,
- Temperatures that encourage vigorous microbial activity.

The composting process is robust, and many aspects of it are inexact. The process occurs over a wide range of conditions and with many feedstocks. The speed of composting and the qualities of the finished compost are largely determined by the

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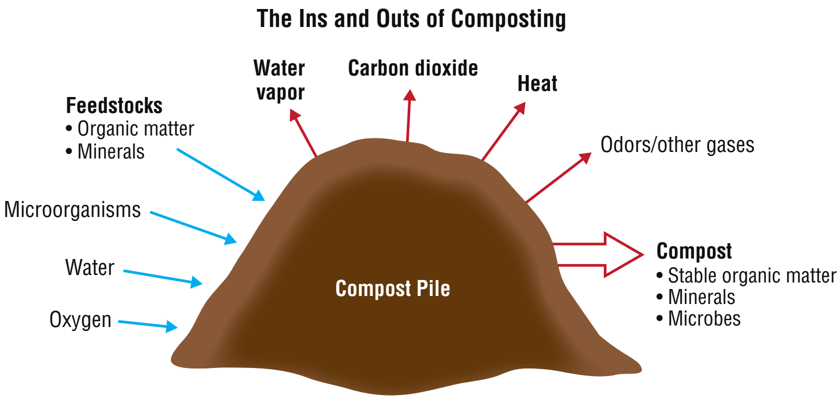

FIGURE 3.1

The composting process.

FIGURE 3.2

A composting pile generates heat, moisture, and CO_2, which are released to the pile's surroundings.

selection and mixing of feedstocks and influenced by the process conditions maintained.

The principles of composting have been well known for years, but continue to be scrutinized and fine-tuned by research and practice. Along the way, accepted theories,

Table 3.1 Favorable conditions for composting.

Condition	Reasonable range[a]	Preferred range
Moisture content	40%–65%	50%–60%
Carbon to nitrogen (C:N) ratio	20:1–60:1[b]	25:1–40:1
Oxygen, minimum concentration within the interior pore spaces	Greater than 5%	Greater than 10%
Temperature[c]	45–70°C (113–160°F)	50–65°C (120–150°F)
Ph	5.5–9.0	6.5–8.0
Particle size	3–50 mm (1/8 to 2 in.)	Depends on feedstocks and use for compost
Bulk density	Less than 700 kg/m^3 (1200 lbs/yd^3)	400–600 kg/m^3 (700–1000 lbs/yd^3)

[a] *Generally for rapid composting. Composting can still be successful outside of these ranges.*
[b] *Some feedstocks can be composted successfully even at C:N ratios greater than 60:1, although the composting rate is slow and the time period is long.*
[c] *Temperatures as low as below 45°C are conducive to rapid composting, but sanitization specifications require temperatures to be held at 55°C or above for a period of time (e.g., three days). See Section 4.10.*

principles, and practices have been summarized in influential references, including but not limited to Howard (1935), Waksman (1939), Rodale (1971), Gouleke (1972), Gray et al. (1973), Jeris and Regan (1973), Poincelot (1975), Willson (1980), Haug (1980 and 1993), Epstein (1997), BioCycle magazine (and its predecessor Compost Science), and numerous conference proceedings (e.g., Gasser, 1985; Hoitink and Keener, 1993). Drawing generously from these and more recent sources, this chapter presents the current knowledge about the composting process and the factors that influence it.

2. What happens during composting?

Composting begins as soon as moist organic materials are piled together. Decomposer microorganisms (bacteria and fungi) are already present on the surfaces of every particle and plenty of oxygen is available. Almost immediately, the microorganisms start increasing in numbers. They use the readily available sugars, starches, and proteins as food, providing the energy and compounds they need for growth and metabolism. As the process continues and the easily degradable organic substances are depleted, the composition of the microbial populations shifts toward species that are better adapted to metabolize the more difficult organic compounds.

Organic materials used in composting contain a significant amount of stored energy. The original source of this energy was the transformation of solar energy to chemical energy during photosynthesis in plants. By breaking the chemical bonds, microorganisms obtain energy for growth and synthesis of nutrients from the organic materials. During this process, some of the chemical energy is transformed to heat.

The composting feedstocks themselves act as insulation, slowing the dissipation of heat. When heat is generated faster than it is lost, the temperature of the pile rises. The temperatures can continue to rise until microorganisms are inhibited or die. The overall process is complex and dynamic where different sets of microorganisms thrive, die, and become food for others as they attack various components of the feedstocks over a range of temperatures.

In aerobic systems, energy production is proportional to the amount of oxygen consumed. Rapidly decomposing feedstocks consume a great deal of oxygen and produce abundant heat. Since the release of heat is directly related to the microbial activity, temperature is usually a good indicator of how well the process is working. An increase in temperature as a result of microbial activity is typically noticeable within a few hours of forming a pile or windrow. The temperature of composting material characteristically follows a pattern of rapid increase to 50−71°C (120−160°F), which can be maintained for many weeks. As active composting slows, temperatures gradually drop toward 40°C (100°F) and finally to near ambient air temperature. The activity, and thus the temperature, may fall due to poor aeration, low moisture, or lack of nutrients and then recover when these deficiencies are corrected by agitation, resupply of oxygen, or the addition of water. This characteristic pattern of temperature rises and fall over time reflects changes in the rate and type of decomposition taking place as composting proceeds and also reflects the "stability" of the organic matter in the compost (Fig. 3.3).

During composting, a wide range of temperature, moisture, and oxygen conditions can exist within the pile, even at a given point in time. The surface is near ambient temperature, oxygen, and humidity while the interior could be hot, oxygen depleted, and very moist. Beneath the surface, the conditions vary within the composting mass because the pile is not homogeneous and some areas possess or receive more moisture, nutrients, and air than other locations. This variation of conditions within the composting mass is reduced by mixing and moderated by containment, such as composting within vessels or under covers. The conditions change as the feedstocks decompose and as the pile is managed and manipulated. As the initial oxygen present in the pile is consumed, aerobic decomposition slows and may eventually changeover to mostly anaerobic if the oxygen is not replenished.

Microorganisms obtain their oxygen from air via *aeration*—ventilation for the composting piles. Aeration is required to recharge the continually depleting oxygen supply and to vent carbon dioxide and other gasses that accumulate in the pore space. Aeration is provided either by *forced aeration* or by passive air exchange (natural convection and diffusion). Mechanical mixing of the composting materials, or turning, temporarily supplies fresh air and oxygen; but this oxygen is quickly consumed and must be replenished by passive or forced air movement.

Through the active composting period, falling temperatures indicate decreased microbial activity. The microorganisms may become less active because the nutrients they need become depleted or unavailable, because they do not have enough moisture, or because they are not getting the oxygen they need. Oxygen flow may be insufficient because the pores between the particles are too small (the bulk density

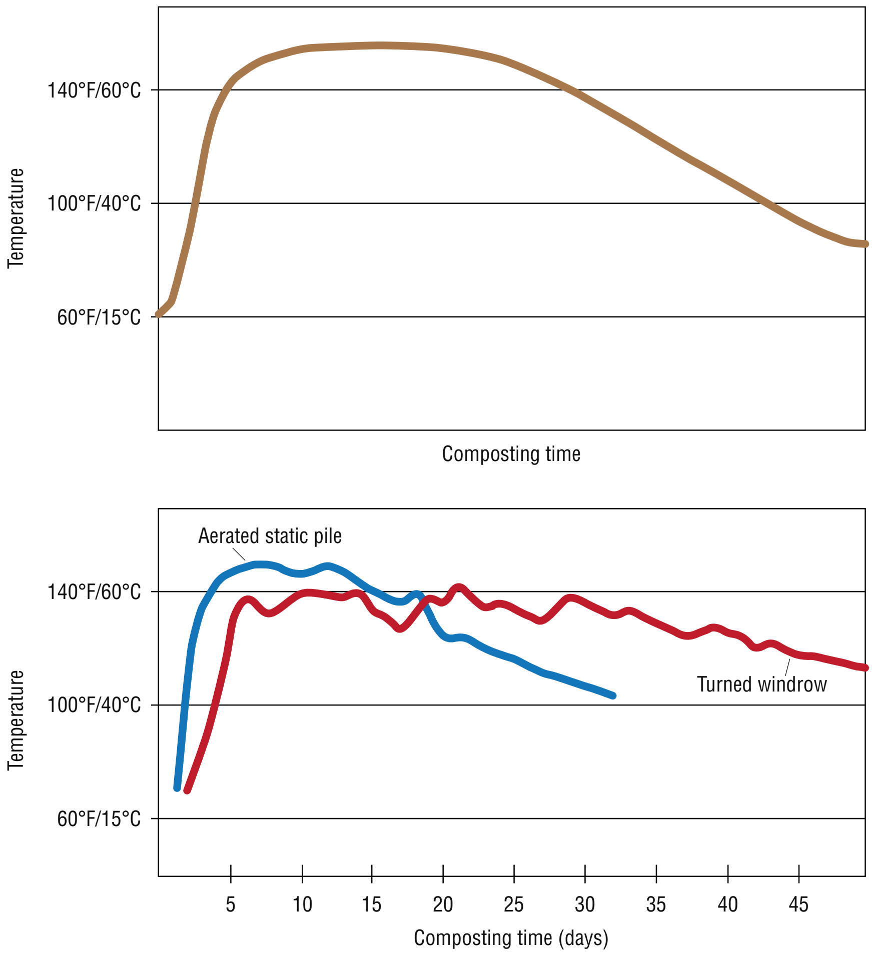

FIGURE 3.3

Temperature-time patterns for composting—generalized (top) and typical (bottom).

is too high), because the pores are filled with water, or because the pile is too big. Under these conditions, decomposition continues anaerobically and generates unwanted odorous compounds. On the other hand, if oxygen is available and the microbial activity is intense, the temperature can rise well above 60°C (140°F). As temperatures climb above 65–70°C (150–160°F), many microorganisms begin to die or become dormant (Strom, 1985). Cooling the pile by forced aeration or reducing the pile size helps to keep the temperature from reaching these damaging levels. Turning the pile is not a reliable cooling method during the vigorous phases of composting. Turning generally stimulates composting in the active phase. After an initial drop following turning, temperatures tend to recover, and often increase beyond the previous level. In the later stages, turning may have a lasting cooling effect—an indication that the active stage is ending.

A curing or maturation stage follows the active composting stage. In the curing pile, the compost continues to decompose but at a much slower pace and typically at lower temperatures. The rate of oxygen consumption decreases to the point where natural convection and diffusion usually meet the oxygen demand without forced aeration. However, curing piles are sometimes turned and/or aerated with blowers to ensure that aerobic conditions and moderate temperatures are maintained throughout the pile and odorous conditions to not occur.

The composting process does not stop at a particular point. Material continues to break down slowly. The nutrients from the original feedstocks become bound within the microbial community and its byproducts and continue to be slowly recycled. Compost is judged to be "done" by process indicators like temperature decline, oxygen demand, carbon dioxide evolution, and ammonia/nitrate concentrations. Compost manufacturers also use characteristics related to the compost's use and handling, such as texture, color, moisture, and odor. The degree of doneness is called its maturity. Mature compost is stable; that is, it has a low level of biological activity and will not cause harm to growing plants due to continued decomposition. However, the compost's usefulness can be limited by other factors unrelated to the compost's stability, such as soluble salts (Chapter 15).

3. Changes in the materials during composting

During composting the microorganisms transform organic feedstocks into compost (Fig. 3.4). This transformation changes the nature of the materials. The feedstocks

(A) (B)

FIGURE 3.4

Composting changes the nature of the materials from a collection of diverse feedstocks into a uniform easily handled product.

begin as a diverse mixture of particles and compounds, many of which are easily degraded and potentially odorous, others highly resistant to decomposition, and many on a spectrum between those two extremes. By the time composting is complete, the mix of compounds becomes more uniform and significantly more stable. Little or no trace of the original feedstocks is discernible, with the common exception of wood particles (and inert components). The material becomes dark brown to black in color. The particles reduce in size and become consistent and soil-like in texture. In the process, the amount of humus-like compounds increases, the carbon:nitrogen (C:N) ratio decreases, the bulk density increases, and the nutrient exchange capacity of the material increases.

Composting leads to both a large weight reduction, typically on the order of 40% to 50%, and a substantial shrinkage in volume, of one-half to up to 90% of the initial volume. Part of this volume reduction represents the loss of mass, as CO_2 and water escape to the atmosphere. However, much of it occurs as loose, bulky raw feedstocks break down into crumbly, fine-textured compost. Where a particular feedstock mixture falls in this spectrum depends upon the specific feedstocks and, to a lesser extent, on the methods of composting and processing. High moisture, readily degradable materials like vegetative food residuals, and loose bulky feedstocks like leaves, exhibit the greatest loss in volume. A volume reduction of 75% to 90% is not uncommon for leaves and mixed food scraps. Typical agricultural materials, like manure, exhibit a more moderate shrinkage, generally finishing at 30% to 70% of the original volume (Larney et al., 2008).

Fig. 3.5 shows dry mass and volume reductions of several different feedstock mixes after 100 days of turned-windrow composting (Breitenbeck and Schellinger, 2004). The largest percentage volume losses are associated with bulky vegetative materials. From these results, the authors generated the following regression formula ($r = 0.72$) relating volume loss (ΔV) to initial dry bulk density (dBD_i).

$$\Delta V = 0.80 - (2.0 \times dBD_i) \tag{3.1}$$

The C:N ratio gradually falls during composting because of the loss of carbon as CO_2 from the starting materials. The amount of carbon lost during composting usually exceeds the nitrogen loss. However, if the starting C:N ratio is low, less than 15:1, the nitrogen losses may be large enough to cause little change in the C:N ratio.

Some loss of nitrogen from the composting pile is inevitable. Significant amounts of the nitrogen in the feedstocks can also be lost as ammonia and, to a lesser extent, as nitrous oxides. Nitrogen loss increases with lower starting C:N ratio, higher temperatures, higher pH, and more frequent turning. Thus, composters with a goal of nitrogen conservation should manage their system accordingly (Chapter 9).

Most other nutrients that are released from the feedstocks during decomposition remain in the compost. They become part of the bodies of new microorganisms or

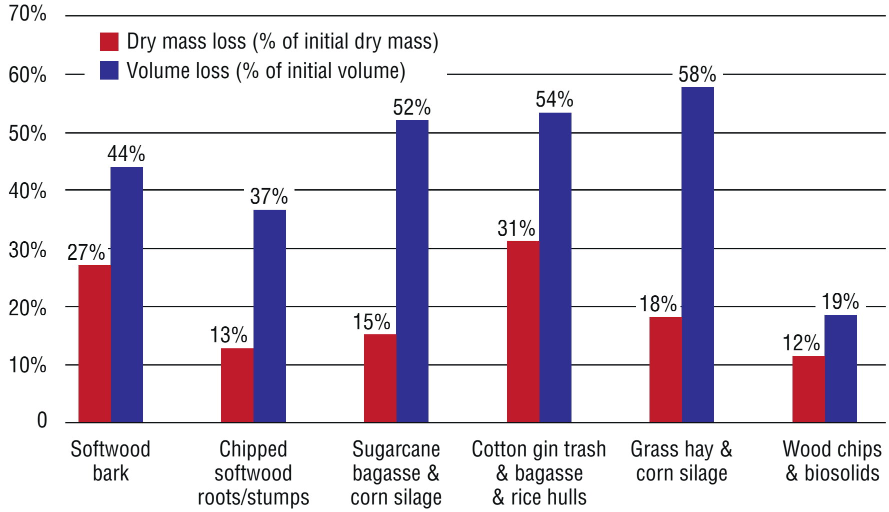

FIGURE 3.5

Reductions in dry mass and volume of several feedstock mixes after 100 days of turned-windrow composting. Mix ratios: 100% shredded softwood bark; 100% shredded softwood root balls and stumps; equal volumes of sugarcane bagasse and spoiled corn silage; equal volumes of cotton gin trash, bagasse, and rice hulls; two volumes of grass hay plus one volume of spoiled corn silage; and four volumes of wood chips plus one volume of biosolids.

Based on data from Breitenbeck and Schellinger (2004).

are incorporated into stable forms of organic matter. As carbon is lost, nutrients become concentrated in the finished compost. However, in areas of high rainfall, potassium, and some phosphorous, can be lost by runoff and leaching.

Microorganisms decompose organic materials progressively, attacking simple sugars and starch first, then proteins, and eventually the larger complex polymers like cellulose and hemicellulose. Microorganisms break down raw materials into simpler compounds, then reform some of them into new complex compounds, while modifying other compounds such as lignin to form humic and fulvic acids. The final product has a low rate of microbial activity but is still rich in microorganisms and the remains of microorganisms.

Some organic compounds present initially in the feedstocks pass through the composting process with little or no change. Lignin, found in woody materials, is difficult to break down in the typical time span of a composting pile. Lignin and other biologically resistant substances are concentrated in the compost. They are partially responsible for compost's characteristic qualities.

4. Factors affecting the composting process

The compost pile is initially made up of a mixture of solid particles of feedstocks with pores spaces between the particles filled with water, air, and other gases. One can envision a microscopic situation in which each solid particle is surrounded by a liquid film, with gases occupying the pore space between the particles (Fig. 3.6). Most of the aerobic decomposition of composting occurs within this liquid film, especially near the surface of the particles where the nutrients are concentrated. Oxygen moves readily as a gas through the air-filled pore spaces but diffuses very slowly through the liquid and solid portions of the particles (Van Ginkel et al., 2002). A population of aerobic microorganisms builds up in the liquid layer surrounding the surface of particles. The microorganisms use the available oxygen dissolved in the liquid film as they decompose organic compounds near the particle's surface (Bemal et al., 1998). Meanwhile microorganisms also are active in the oxygen-starved interior of the particle. The particle shrinks as the composting microorganisms work their way inward.

Factors that affect how quickly the composting process transforms these feedstock particles into compost include: oxygen, aeration; moisture; nutrients (e.g., carbon and nitrogen); feedstock degradability, porosity, free air space (FAS), permeability, structure, bulk density, and particle size and shape; pH; temperature; and time. Many of these factors are interrelated and all impact the rate of decomposition.

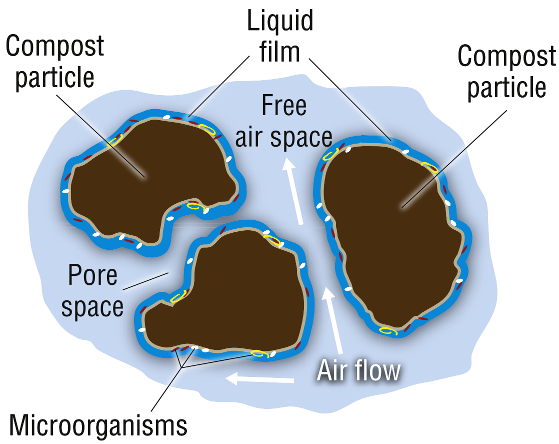

FIGURE 3.6

Depiction of particle environment within composting pile.

4.1 Oxygen

Aerobic composting consumes large amounts of oxygen. For example, one cubic foot of yard trimmings may ultimately require all of the oxygen in 10,000 cubic feet of air for the conversion of organic carbon to CO_2. During the initial days of composting, readily degradable components of the feedstocks are rapidly metabolized. Therefore, the need for oxygen and the production of heat, water vapor, and other gases are greatest at early stages. After peaking, typically early in the process, the composting rate and oxygen consumption decrease as the process ages to a relatively steady level near the end, as depicted in Fig. 3.7. A similar pattern can be expected after a pile is turned. The graph is a very generalized illustration of the pattern of microbial oxygen demand. The shape of the curve and time scale depends greatly on the feedstocks and other conditions.

If oxygen is not replaced at the rate it is consumed, the composting process becomes anoxic or anaerobic. Anoxic means that the oxygen levels are low and limit aerobic respiration. Anaerobic technically refers to the absence of oxygen, although the term is generally used to describe both anoxic and anaerobic conditions. In either case, the rate of decomposition slows, and odorous compounds accumulate (Box 3.1).

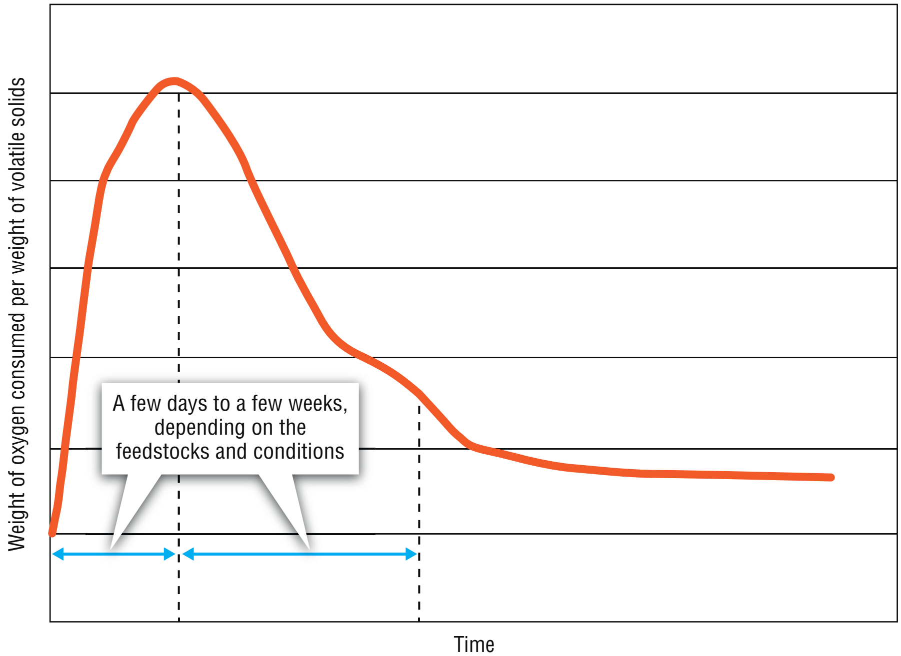

FIGURE 3.7

General pattern of oxygen consumption (i.e., uptake rate) during composting.

Box 3.1 Why the stink?

Author: Tom L. Richard

Although some plants and animals produce odors as a repellant, to the best of our knowledge microorganisms are not intentionally using this strategy to gain privacy from prying eyes. Instead, odors are an inherent byproduct of their metabolism, especially the anaerobic respiration and fermentation processes that provide them with energy. Microorganisms liberate the energy needed for metabolism and growth by combining electron donors (carbohydrates, proteins, fats, etc.) with electron acceptors, a process commonly referred to as respiration. A compound that accepts electrons takes on a negative charge and is thus said to be "reduced." In aerobic respiration, oxygen serves as the electron acceptor. Oxygen is the most energy-efficient electron acceptor, resulting in the most "complete" decomposition and providing a competitive advantage to aerobic organisms. Nitrate (NO_3^-) is a close second and thus readily consumed under low oxygen conditions (i.e., anoxic).

Under anaerobic conditions, sulfate (SO_4^{-2}), and carbon dioxide (CO_2) and minerals such as ferric iron (Fe^{+3}) and manganese (Mn) also serve as electron acceptors, but with significantly lower amounts of energy released. The reduction of sulfate produces the gas hydrogen sulfide (H_2S) and leads to other odorous sulfide gases including dimethyl sulfide and dimethyl disulfide. Other anaerobic reactions recycle part of the carbon liberated during anaerobic degradation as an electron acceptor, producing a biogas that includes both CO_2 and methane (CH_4). Energy can also be liberated anaerobically through fermentation, which uses organic molecules as both electron donors and electron acceptors. Fermentations can produce a variety of compounds (including hydrogen gas and alcohols), but of particular interest, here is the production of organic acids, many of which are very odorous and toxic to plants.

Because they do not liberate all the energy from the feedstocks, anaerobic respiration and fermentation leave useable energy in the products of decomposition (e.g., methane, acetate). Thus, aerobic organisms can break down the products of these anaerobic processes to extract more energy. Also, anaerobic respiration and fermentation yield products like methane and ethanol, which can be harvested from these processes as alternative fuels.

Although respiration reactions produce and consume the largest quantities of odors, ammonia (NH_3) can be odorous and forms under both aerobic and anaerobic conditions. Urea is another common source of ammonia. Also, protein degradation produces ammonia as the amino acids are broken down (i.e., deamination). Ammonia is particularly volatile under alkaline (high pH) conditions, when it readily escapes from the composting pile.

Respiration and fermentation reactions using the example of glucose ($C_6H_{12}O_6$):

Aerobic respiration (oxygen serves as the electron acceptor to form only carbon dioxide and water):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Anaerobic respiration (sulfate is the electron acceptor, forming odorous hydrogen sulfide):

$$C_6H_{12}O_6 + 3SO_4^{-2} + 6H^+ \rightarrow 6CO_2 + 6H_2O + 3H_2S$$

Fermentation (glucose decomposes without an external electron acceptor to form odorous butyric acid and hydrogen gas):

$$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH_6 + 2CO_2 + 2H_2$$

Fermentation (glucose decomposes without an external electron acceptor to form ethanol):

$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$$

Anaerobic decomposition involves different biochemical reactions and a different set of microorganisms. Anaerobic processes are less efficient than aerobic processes, leaving behind a variety of "intermediate" compounds that can further decompose if oxygen is present. Little heat is generated to evaporate water from the materials. Anaerobic processes produce a variety of volatile intermediate compounds, including methane, organic acids, hydrogen sulfide, and other substances. Many of these compounds have strong odors, and some are toxic to plants (phytotoxic). Under anaerobic conditions, these compounds accumulate and can be released to the environment in noticeable concentrations, especially when the pile is turned, aerated, or otherwise disturbed. If oxygen becomes available or the compounds migrate to an area in the compost pile where oxygen is available, they can oxidize to inoffensive compounds like carbon dioxide and water. An adequate supply of oxygen gives the more efficient aerobic organisms a competitive advantage over the anaerobes. Thus, maintaining aerobic conditions is important in avoiding the offensive odors associated with anaerobic decomposition.

Although composting is called "aerobic," it is more accurate to say that composting is *predominantly* aerobic, rather than exclusively aerobic. The availability and distribution of oxygen varies within different sections of any given pile or vessel. Also, the average level of oxygen varies among different composting methods and operations. But even in well-aerated systems, part of the organic matter likely decomposes anaerobically. The critical factor is that enough oxygen is present such that most of the anaerobic compounds eventually decompose aerobically before leaving the pile. In composting, aerobic conditions should prevail—enough to degrade odorous compounds to a tolerable level and enough to render the compost largely free of phytotoxic compounds.

In the early stages of the composting process, the rate of oxygen consumption can outpace the rate at which it can be replenished. Therefore, the oxygen levels can be low at the start of composting and then recover as the decomposition rate and oxygen demand decline. Correspondingly, the carbon dioxide concentration shows the reverse pattern (Fig. 3.8).

The numerical oxygen concentration that divides aerobic and anaerobic states is both indistinct and debated. The minimum oxygen concentration traditionally recommended for aerobic composting is 5%. This value generally refers to the concentration of oxygen in pore spaces within an active pile, windrow, or vessel, although supporting research measured it in the exhaust from laboratory reactors (Schulze, 1962). In comparison, fresh air contains about 21% oxygen.

Although the 5% threshold is still widely observed, the targets for minimum oxygen concentration have increased in recent years. Recommendations for minimum oxygen concentrations now favor 10%, and some recommendations are as high as 18%. This large range is due to several factors including differing philosophies about composting and compost, differing risks and sensitivities to odors, the cost of supplying oxygen and differences in the methods and time constraints of composting. Some composters believe that the quality of the compost suffers whenever anaerobic conditions exist and thus try to maintain oxygen concentrations above 10% (or CO_2 concentrations below 11%). In other cases, a higher oxygen concentration threshold, in the 10% to 18% range is maintained for process and odor control. These cases might include situations where the consequence of odor is severe or compost must be produced quickly and the composting method accommodates rapid

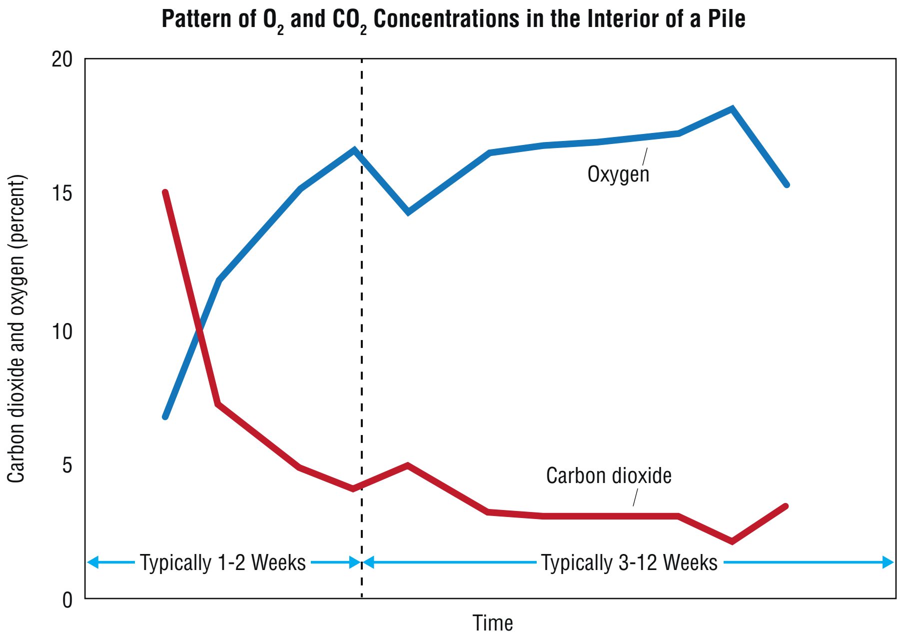

FIGURE 3.8

Common pattern of oxygen carbon dioxide concentrations in a pile due to decreasing decomposition rate.

Adapted from Epstein (1997).

decomposition. Conversely, lower oxygen concentrations are tolerated where odors are not a large concern, and a slower composting method is tolerated.

Maintaining a high concentration of oxygen during the active phases of composting is a challenge. Passively aerated piles, including windrows, can show near zero concentrations of oxygen in the core of the pile, especially in the early stages of composting. Higher oxygen concentrations can be achieved only by limiting pile size and using feedstocks with sufficient FAS for effective convection. With forced aeration composting, oxygen concentration can be maintained more easily because of the control afforded by the fans. However, increasing the rate of forced aeration has drawbacks including energy consumption and potentially excessive loss of heat and moisture (see following section). Ultimately, the most practical oxygen management strategy is dictated by the individual site characteristics, including pile density, moisture, feedstocks, cost of aeration, wind and topographic conditions, and distance to neighbors.

Some compost operators monitor oxygen as well as pile temperatures and odors to learn how these factors relate in their particular system. Various sensors and probes can be used to measure the oxygen concentration in the pore space within a pile. Oxygen can be monitored by using a sensor that reads oxygen directly, or by using a carbon dioxide meter. Carbon dioxide (CO_2) is produced in direct proportion to the oxygen (O_2) being consumed. These devices are described in Chapter 12. Oxygen or carbon dioxide sensors are probably the second most common piece of monitoring equipment at composting operations (thermometers are overwhelmingly first).

4.2 Aeration

Oxygen is supplied to the composting organisms with fresh air.[1] The air is delivered via aeration—either forced or passive.

With forced aeration, mechanical blowers or fans, with a network of pipes, push or pull air through the composting materials (Fig. 3.9). As the air moves through the pile, it delivers oxygen and removes water, heat, carbon dioxide, and other gasses produced within the pile, including odorous gases. The air also cools the pile, primarily by evaporating water. With positive aeration fans push air into and through the pile. Positive aeration is the more energy-efficient direction. The advantage of negative aeration, even though it requires more energy, is that the exhaust air from the pile is concentrated in the outlet of the fan and can be treated for odors.

Passive aeration relies on natural forces to exchange air between the interior of the composting mass and the surrounding environment (Fig. 3.10). The principal force in passive systems is thermal convection—the movement of warm gas upwards due to a decrease in their density as they warm. In rising out of the pile, the exiting gas creates a partial vacuum and cool fresh air flows in to replace it (aka the "chimney effect"). The rate of thermal convection depends on the temperature difference between the gases inside the composting mass and the ambient air plus the resistance to air flow within the material (i.e., permeability). Convection increases with high temperatures within the pile, cool ambient temperatures outside, and an open porous

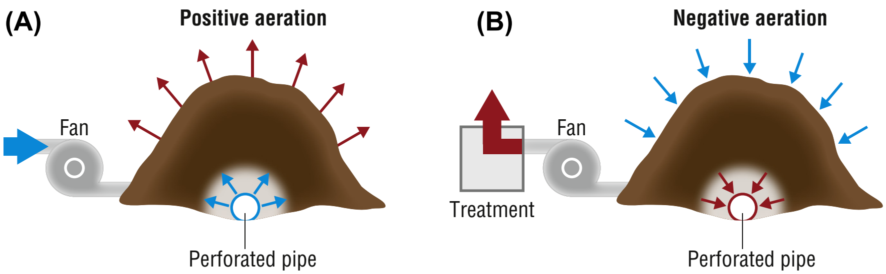

FIGURE 3.9

Forced aeration of a composting pile by positive (A) and negative (B) modes.

[1] Although attempts have been made to directly supply pure molecular oxygen, they have not yet been economically successful.

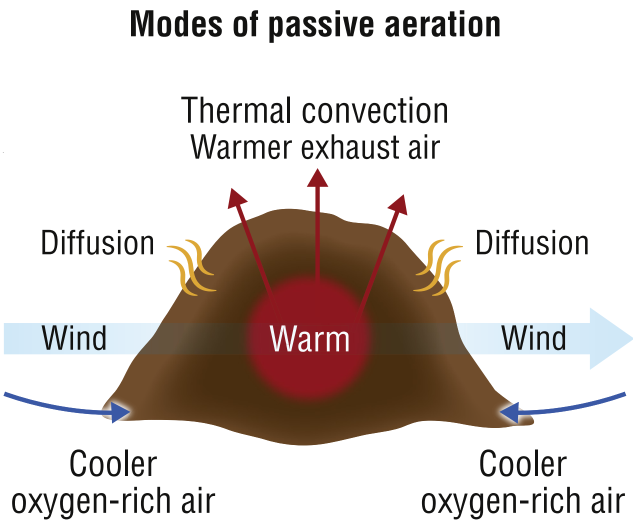

FIGURE 3.10

Driving forces for passive aeration. Passive air flow is primarily caused thermal convection. Molecule diffusion and wind-driven air movement are less consequential.

matrix of materials. Passive aeration also occurs by molecular diffusion, the migration of molecules from areas of high concentration to low concentration due to random molecular movement. Oxygen diffuses into composting materials because there is an imbalance—more oxygen outside than inside. Similarly, carbon dioxide has tendency to diffuse outward. As oxygen levels decrease and carbon dioxide levels increase in a pile, the concentration difference widens and movement due to diffusion increases. Diffusion is a relatively slow means of providing oxygen, especially within wet materials. Finally, in open outdoor windrows and piles, wind can assist in forcing gases into and out of the composting mass.

In addition to providing oxygen, aeration removes heat, water vapor, and other gases from within the composting materials. In fact, the required rate of aeration for heat removal (i.e., temperature control) can be 10 times greater than that for supplying oxygen. Therefore, temperature control, instead of oxygen supply, usually dictates how much, and how frequently, forced aeration is required. As noted earlier, the need for oxygen and the generation of heat, water vapor, and other gases are greatest early in the process. Therefore, the required rate of aeration also is greatest at the start and progressively declines as the feedstocks decompose.

4.3 Turning

"Turning" is the common term for the agitation or mixing of materials in compost piles, bins, vessels and, especially, windrows (Fig. 3.11). Turning is performed

FIGURE 3.11

Tractor-powered windrow turner in action.

intentionally to stimulate composting by homogenizing the composting materials. It occurs incidentally when materials are moved from one location to another, sometimes between two distinct stages of composting. Turning invigorates the composting process, but it is not a reliable means for aerating or cooling piles (Box 3.2).

Turning blends the composting materials and moves them to and from hotter and cooler areas. Turning overcomes the stagnation that can occur in static composting systems because materials are not completely homogeneous and passive aeration is not uniform. It can eliminate localized limitations due to too little or too much moisture, lack of particular nutrients, air channels, or other process factors. Turning breaks apart particles, mixes feedstocks, and promotes more even decomposition and pathogen destruction. The overall effect of turning is to stimulate composting.

The effects of turning on the composting process have been demonstrated by several illumining studies, including but not limited to Buckner (2002), Michel et al. (1996) and Michel and Tirado (2010). Such studies have shown that higher turning frequencies increase the rate of decomposition, pathogen destruction, and compost bulk density. Generally, more frequent turning decreases compost particle size and the time required to reach full maturity and also reduces the potential phytotoxicity of composts. Beyond a certain point, however, turning has only a modest effect on increasing the composting rate. Daily turnings usually do not decrease the time required to stabilize compost, compared to biweekly turning or even turning every two weeks. Studies have also shown that turning frequency has minimal *long-term* effects on oxygen concentrations or temperatures within windrows or on final compost properties (Chapter 5). Windrow turning frequency appears to have less of an impact on the composting process than other variables such as feedstock composition (e.g., C:N ratio), moisture content, and pile size.

Box 3.2 Compost turning: falsehoods, facts, and functions

- Turning provides aeration: False! The oxygen introduced by mechanical agitation (turning) may be consumed in a matter of minutes in an active pile. Passive or forced aeration is needed to sustain oxygen levels after turning.
- Turning "fluffs" the pile and restores pore space: False! (Mostly) Depending on the feedstocks and type of turning equipment, turning tends to reduce particle size, which increases bulk density and reduces total pore space. Turning can temporarily increase the porosity of materials that are already dense (e.g., cattle manure) but materials eventually resettle and compact.
- Turning cools the pile: False! (Mostly) During the active phase of composting, turning reduces temperature only temporarily. Generally, it is followed by an increase in temperature beyond the preturning point by exposing fresh surfaces for decomposition and breaking up anaerobic pockets. During the later phase of composting, when heat generation slows, turning can have a permanent cooling effect.
- Turning speeds decomposition: Fact! Turning has an invigoration effect on the composting process, even when forced aeration is applied. It releases trapped gases, exposes fresh surfaces, breaks apart clumps, and redistributes moisture, nutrients, and microorganisms. Because turning performs these functions, the composting process tends to surge forward after turning. Each turning advances and accelerates the process in such surges. However, as the turnings increase in frequency, each successive turning has a smaller effect. Each composter must decide when the positive effects of turning are outweighed by the costs.

The advantages of turning can extend beyond the composting process to the compost product. Turning with a specialized windrow turner typically shreds and homogenizes the material, thus producing a compost product that is more uniform in texture and moisture. These effects can not only improve screening efficiency but also the compost's appeal to its users. Therefore, even if the composting process does not call for it, many composters continue to turn windrows to enhance product quality.

While turning has a stimulating effect on the process, excessive turning can have some undesired consequences. First, turning can lead to excessive drying and particle size reduction. Second, turning releases ammonia (NH_3) and other gaseous decomposition products that have accumulated in the internal void spaces of the windrow. Some of the products released by turning are odorous. Turning has also been shown to increase nitrogen loss from low C:N ratio feedstocks, like many types of animal manures (Yang et al., 2019). Thus, turning can have detrimental effects by increasing nitrogen loss (principally as NH_3) and odor emissions. Turning windrows and piles more than necessary increases the labor and fuel costs required to produce stable compost and wears out equipment faster.

Finally, and back on the plus side, turning provides access to the interior of a pile or windrow, making it easier to observe and evaluate the progress of decomposition. It provides the opportunity and a means to evenly add water and/or nutrients to the composting materials. In short, turning is an aid to process management.

4.4 Moisture

After the feedstocks themselves, moisture is perhaps the most important factor in the decomposition of organic materials. Without enough moisture, virtually nothing happens. Composting materials should be maintained at a moisture content between 40% and 65%, depending on the feedstocks and stage of composting. The preferred range is narrower, between 50% and 60%. Too little moisture slows biological activity, even to a halt, while too much moisture interferes with aeration and oxygen transfer. In theory, biological activity is optimal when the materials are saturated and oxygen is plentiful. While this situation might be achieved in liquid composting systems by bubbling in air and continuously mixing, the costs would be very high. Thus, composting solid feedstocks at roughly 40% to 65% moisture, balances the microorganisms' need for abundant moisture and the ability to economically supply them with oxygen.

Water is essential to biological activity. The moisture that envelopes particles in the compost pile supports the metabolic processes of the microorganisms. Water provides the medium for chemical reactions, dissolves and transports nutrients, and allows the microorganisms to move about.

However, aerobic microorganisms also need oxygen. The oxygen in the air between the particles must dissolve into the water around each particle and then move by diffusion to the microorganisms. As the moisture content increases, the film of liquid surrounding the solid particles grows thicker and oxygen and carbon dioxide diffuse more slowly into and out of the film (Fig. 3.12). Because oxygen diffuses 10,000 times slower in water than in air, a thicker moisture layer results in more anaerobic activity. As the lower diagram of Fig. 3.12 illustrates, a thick water film limits the penetration of oxygen to the solid substrate. With limited oxygen, the resulting anaerobic compounds break through to the pore space before completely decomposing. The odors may be decomposed within the pile or they may be carried out of the pile with the exhaust or liberated at turning.

In addition, at high moisture levels, generally greater than 65%, water displaces much of the air in the pore spaces of the composting materials. The water in the pores reduces air movement into and through the pores and further encourages anaerobic conditions. The abundant moisture also adds to the weight of the materials, which causes more settling, compaction, and loss of pore space within the pile. As a result, air movement through the pores is impeded. In short, too much moisture interferes with aeration and leads to anaerobic conditions.

On the other hand, insufficient moisture negatively affects the decomposer organisms. Biological activity essentially ceases below 15% moisture content, but experience has shown that the composting process becomes noticeably slower as the moisture content drops below 40%. For rapid composting, 50% moisture is usually a better lower limit, depending on the feedstocks and phase of composting. Composters often allow moisture to drop below 50% during the later phase of composting to create a drier product that is more easily screened.

Since the moisture content tends to decrease as composting proceeds, the moisture content of the blended feedstocks should start above 50%. For many compost mixtures, materials that are too dry are blended with materials that are too wet to achieve the target moisture content. With some dry materials, such as leaves, water

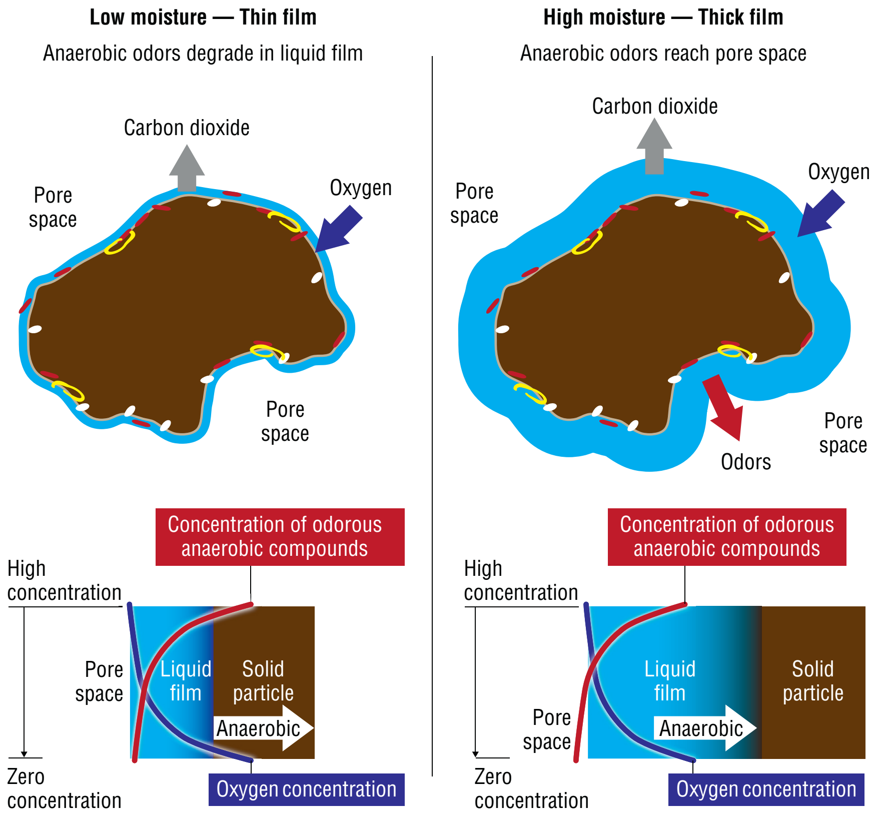

FIGURE 3.12

Effect of high moisture on oxygen transport and diffusion.

Based on presentation by Tom Richard and Cary Oshins.

may be added directly. As a source of moisture for dry feedstocks, some composters are able to obtain liquid wastes, such as wet manure, food processing residuals, and even out-of-date beverages.

During composting, moisture levels are constantly changing. Water may be added as rain or snow, released from cells as they degrade, or intentionally added with a watering system. Moisture decreases as respiration transforms liquid water to water vapor and as water evaporates from the pile. Usually more water evaporates than is added by microbial respiration and precipitation, so the overall moisture content tends to decline as composting proceeds. However, the moisture balance depends on heat production within the pile, seasonal and short-term weather patterns, and the pile size and exposure. Moisture levels should be monitored and maintained such that materials are thoroughly wetted without being waterlogged or dripping excessive water.

The 40%–65% moisture content range is a general recommendation that works well in practice for most feedstocks. The acceptable moisture limits depend on the particle size, porosity, absorbency, and ash or mineral content of the feedstocks.

Highly porous materials with large particles can be wetter than densely packed materials with small particles. A mixture with highly absorbent materials may need to be maintained well above 50% moisture to support rapid composting. Feedstocks that contain a high amount of inert (nonbiodegradable) material compost well at moisture contents below 50% because it is only the noninert fraction that is decomposing. Examples include animal manure with a lot of soil and a municipal waste with plastic. In such cases, the "ash-free" moisture content can be used as a guide (Chapter 4). An ash-free moisture content in the range of 50% to 60% generally works well for composting.

4.5 Nutrient and the carbon to nitrogen (C:N) ratio

Carbon (C), nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) are the primary nutrients required by the microorganisms involved in composting. N, P, and K are also the primary nutrients for plants, so their concentrations can also influence the value of the compost as a fertilizer. Manures, biosolids, plant residues, and food residuals contain ample quantities of most nutrients to nourish the microorganisms. The nutrients that mainly influence the composting process are carbon (C) or nitrogen (N), either in excessive or insufficient amount. A balanced supply of C and N (i.e., a good C:N ratio) usually ensures that the other required nutrients are present in adequate amounts. However, the lack and abundance of P and S have occasionally been found to substantially affect the process.

4.5.1 C:N ratio

Carbon is the basic building block of virtually all organic compounds, so it is the major element in all compost feedstocks. Microorganisms use carbon compounds for both energy and growth, just as humans do. Nitrogen is an essential element for the production of protein and for cellular reproduction. In general, living organisms, from bacteria to humans, contain 10 to 15 units of carbon for each unit of nitrogen, by weight. However, because organisms continually respire and lose carbon as CO_2, they need to consume about 25 times more C than N. It is, therefore, important to provide C and N in appropriate proportions at the start of the process. The ratio of carbon to nitrogen is referred to as the C:N ratio. The C:N ratio expresses the elemental weight of C present relative to the elemental weight of N present. Typical C and N data for common feedstocks are listed in Appendix C. A feedstock with a C:N ratio that is too low or too high can be blended with other feedstocks to better balance these nutrients.

Individual feedstocks or feedstock blends with a C:N ratio of 25:1 to 40:1 are considered ideal for active composting. In this range, there is usually enough nitrogen to promote the growth and reproduction of microorganisms and sufficient carbon available to sustain the process while also conserving nitrogen. However, initial C:N ratios from 20:1 up to 60:1 consistently result in successful composting.

With C:N ratios below 20:1, composting is rapid but the microorganisms use the available C without converting all of the available N into cellular compounds. The excess N is converted into nonorganic N compounds like ammonia or nitrous oxide, which can volatilize (i.e., evaporate). In this situation, as much as 50% of the total initial N can then be lost to the atmosphere. Establishing a starting C:N ratio above 30:1 does much to retain nitrogen (Fig. 3.13).

The consequence of a high initial C:N ratio (above 40:1) is a slowing of the process because there is not enough N to feed enough organisms to decompose the available carbon. As the C:N ratio increases, the rate of composting generally decreases. However, for most applications, composting proceeds well even with feedstock mixes with C:N ratios up to 60:1. In fact, it can be a good management practice to establish an initial C:N ratio that is higher than the "ideal" for the microorganisms. While the higher ratio may reduce the rate of composting, the slower pace can make the process more manageable and forgiving. In addition, feedstocks with high C:N ratios typically include a good proportion of dry and bulky materials like wood chips, leaves, and sawdust. These materials tend to increase the porosity of the mix, improving aeration and further reducing the risk of odors.

The C:N ratio is an important but imperfect guide for balancing these two nutrients. The types of compounds that contain the carbon atoms must also be considered. Different carbon-containing compounds biologically decompose at different rates (Fig. 3.14). For example, chopped straw decomposes and releases its C to the microorganisms more easily than sawdust. This effect occurs because the straw is mostly cellulose, whereas the carbon compounds in sawdust and woody materials are largely bound by lignin, which is highly resistant to biological break down (Chapter 4). Similarly, the C in the simple sugars of fruit wastes

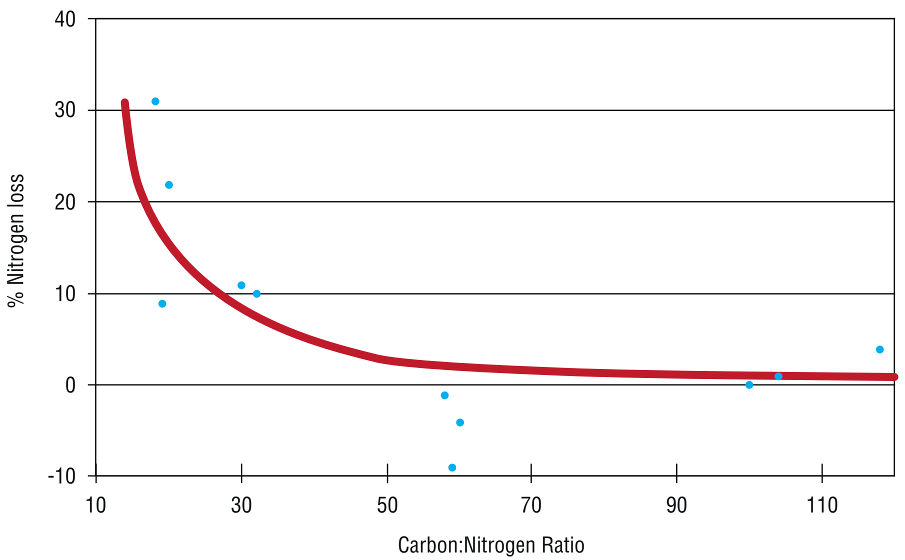

FIGURE 3.13

Effect of C:N ratio on nitrogen retention.

Adapted from data presented by Larsen and McCartney (2000).

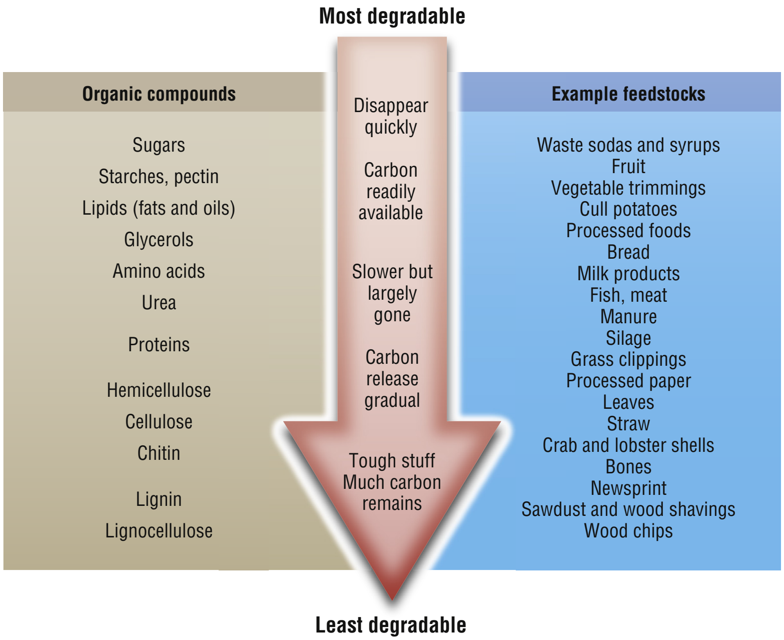

FIGURE 3.14

Relative degradability and carbon-availability of organic compounds.

and the starches of grains is more quickly consumed than the cellulose-carbon in straw. The biodegradability of organic carbon compounds, and their contribution to the composting process, can be estimated by the lignin content. Although it is an uncommon practice, a biodegradability factor can be used to roughly estimate the amount of "available" C and the C:N ratio can be adjusted accordingly. The N in nearly all feedstocks can be considered completely biodegradable during composting.

Finally, providing a mix of feedstocks with an appropriate C:N ratio has a larger impact, beyond the availability of nutrients. Feedstocks that have a high N concentration (i.e., low C:N ratio), like wet grass, unbedded manures or food residuals, tend to be wet, have small particles, and decompose quickly. Feedstocks that have a low N concentration (i.e., high C:N ratio), like branches, bark, or straw, tend to be dry, contain larger particles, and decompose more slowly. Thus, mixing feedstocks to obtain the right ratio of C to N also creates a mix that is more balanced with respect to moisture, particle size, bulk density, porosity, and decomposition rate. In short, a mix with a good C:N ratio is good in many respects. This larger effect of balancing the feedstocks may be more important to how well the composting proceeds than the actual ratio of C to N itself.

Table 3.2 General targets for feedstock starting nutrient ratio (weight of carbon ÷ weight of other nutrient).

Nutrient ratio	Target range
Carbon to nitrogen (C:N)	20:1 to 60:1
Carbon to phosphorus (C:P)	120:1 to 250:1
Carbon to potassium (C:K)	100:1 to 150:1
Carbon to sulfur (C:S)	Approximately or greater than 100:1

4.5.2 Other nutrient ratios: P, K, and S

Although C and N are usually the principal nutrients in the composting process, in some situations, the lack of other nutrients also can affect the process (Table 3.2). If a compost pile that appears satisfactory in terms of C:N and moisture is not progressing as expected, other nutrient ratios may indicate a limiting nutrient.

Several researchers have identified feedstocks in which the addition of P considerably stimulated the composting process. Those feedstocks tend to be dominated by paper products and by-products (e.g., paper mill residuals, municipal solid waste). A recommended ratio of C to P falls in the range of 120:1 to 240:1 (Brown et al., 1998).

Potassium has not been implicated as a limiting nutrient for the composting process. Nevertheless, a C to K ratio of between 100 and 150:1 appears to be a good target, based on microbial biomass composition and carbon conversion.

The ratio of carbon to sulfur (C:S) also is worth noting—not because of a lack of S, but rather its abundance. Organic matter generally has a C:S ratio of roughly 100:1. When the C:S ratio is appreciably lower than 100:1, there is an excess of S relative to the amount of C that the microorganism can use. Just as excess nitrogen forms ammonia, excess S can lead to the evolution of volatile sulfur compounds, many of which are odorous (Miller, 1993). Maintaining a C:S ratio near or above 100:1 might limit the generation of odorous compounds. However, currently there is little guidance from research or actual operations on this practice (Chapter 10).

4.6 Physical factors: particle size, structure, porosity, free air space, and permeability

In addition to providing the chemical compounds for decomposition, the feedstocks also provide the physical foundation for the process. Several characteristics of the feedstocks collectively determine the physical arrangement of particles as they pile up. These characteristics primarily affect the composting process by their influence on aeration. In addition, particle size also affects the microorganisms' access to the organic matter, nutrients and moisture. The physical properties of the pile can be adjusted by the selection of the individual feedstocks and by preprocessing. Preprocessing might include grinding to reduce the size of the particles, mixing to increase homogeneity and screening to change particle size distribution. Feedstocks added to adjust these properties are referred to as amendments or bulking agents.

A compost pile is a collection of solid particles that physically support one another to stack together in a pile. The 3-dimensional matrix of solid particles creates a vast network of voids, or pore spaces. The pores are filled with air, other gases, and liquids, primarily water. The network of pores provides multiple pathways for air to move into and through the compost pile and for gaseous products of decomposition to move through and out of the pile. The pores serve as the pile's ventilation system. The arrangement and size of pores is determined by size and size distribution of particles, the rigidity of the particles (i.e., structure), and the amount of water present. The matrix of pore spaces can be described by several closely related measures including porosity, FAS, and permeability.

4.6.1 Particle size and shape

Microbial decomposition occurs at a particle's surface. As the size of a particle decreases, it has a greater surface area relative to its volume. Therefore, the rate of aerobic decomposition increases with smaller particle size—that is, within limits. Smaller particles pack more tightly together and effectively reduce the size and continuity of pore spaces and generally constrain the flow of gases into and out of a pile. The size distribution and shape of particles also affects aeration. Feedstocks with a broad range of particle sizes and shapes restrict aeration because the small particles fill the voids created by the large ones. Similarly, particles with a uniform shape roughly equal in all dimensions, form larger and more stable pores than long thin or flat particles, while the latter provide greater surface area for decomposition (Fig. 3.15).

The condition of a particle's surface is likewise important. Consider two particles of equal volume and mass, one smooth-surfaced and one rough and jagged. The rough one has considerably more surface area than the smooth one, and therefore decomposes faster since more microorganisms can inhabit the larger surface area.

Size also affects the ability of a solid particle to absorb moisture, and therefore decompose. Small particles are more readily wetted. This relationship is particularly true for materials that are "anisotropic" (i.e., their qualities differ in different directions). For example, a straw stem, which is waxy along its length, takes on water primarily through its ends. Cutting the straw exposes more ends, allows better moisture penetration, and faster decomposition. The same situation applies to some other materials like wood and coated-cardboard.

Optimal particle size is therefore a compromise between available surface area and ease of aeration. The optimal size depends on the specific feedstocks, the method of composting, and the intended market for the product. Good composting results are usually obtained with a variety of starting particles ranging in size from 3 to 50 mm (1/8 to 2 in.).

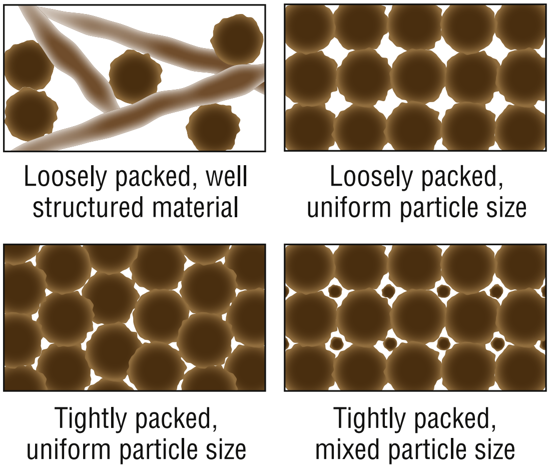

FIGURE 3.15

Effect of particle size and shape on porosity and bulk density.

Source: Richard (1996).

4.6.2 Structure

Structure refers to the rigidity of the particles—that is, their ability to resist settling and compaction. Good structure prevents the loss of porosity in the moist environment of the compost pile, allowing gasses to circulate into and out of the pile. Larger composting piles, especially those that are not regularly turned, require better structure to resist settling and maintain air channels during the entire composting period.

Good structure is provided by feedstocks with large rigid particles that decompose slowly. Ground or chipped wood is the most common amendment used to supply structure. Corn cobs, nut shells, and even inert amendments like chipped tires can be used to supply structure. However, any material must be present in sufficient proportions to substantially support the pile. Increasing moisture levels reduces the rigidity of most materials, although woody feedstocks are less affected than other amendments like straw, cornstalks, and leaves. Amendments added purposely to mainly provide structure are often called "bulking agents."

4.6.3 Porosity

Porosity refers to the nonsolid portion of the composting mass, and includes the space occupied by both the liquid and gases. It does not, however, include the small pore spaces within solid particles. Porosity is determined by the size, gradation, and type of the particles of the materials, and the continuity of the air spaces. It increases with particles that are larger, stiffer (e.g., woodier), more uniform in shape, and when most of the particles are similar in size. Porosity is expressed as percentage of the total volume. A porosity of 60% means that 60% of the volume is occupied by air and water (plus other liquids and gases) while the remaining 40% of the volume is solid particles.

4.6.4 Free air space and permeability

FAS is the portion of pore spaces not occupied by liquids or solids. It is sometimes referred to as the "air-filled porosity," although gases other than air also occupy that space. Like porosity, FAS is expressed as a percentage of the total volume. An FAS of 40% means that 40% of the volume is gases, the remaining 60% is filled with solids and liquids. FAS is the porosity minus the volume of liquids present (Fig. 3.16).

Compared to porosity, FAS is a better indicator of a pile's ability to channel air because it accounts for the presence of water. The FAS essentially determines how easily air can move through the composting mass. In general, the resistance to airflow decreases as FAS increases. Recommended values for FAS range widely from 30% to 60%, although most research has generally favored values between 30% and 40%. In part, the wide range is due to different techniques for measuring FAS (Alburquerque et al., 2008). Currently, field measurements are the most practical means of measuring FAS (see Chapter 4).

If the FAS is low, there is much resistance to aeration, both passive and forced. If the FAS is too high, then the pile temperatures may remain low; possibly because the heat generated by the microbes quickly dissipates. Compression from the overlying material reduces the porosity and FAS near the base of the pile (Fig. 3.17). Porosity and FAS generally diminish during composting as the materials decompose and particles are reduced in size.

FAS is a useful indicator of how well a pile aerates, but it can possibly be deceptive, at least in theory. A feedstock with few large pores can have the same FAS value as another feedstock with many more small pores. On one hand, large pores can be widely dispersed, leaving pockets of anaerobic solids with air flowing around them.

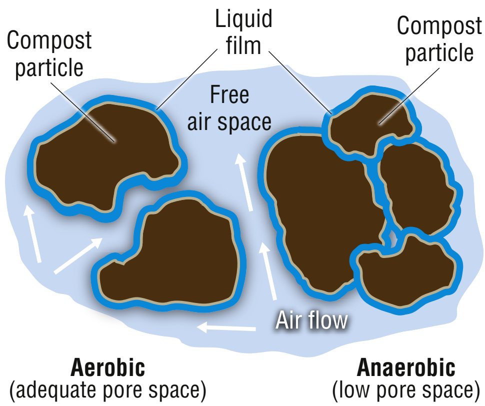

FIGURE 3.16

Conceptual depiction of free air space.

Source: C. Oshins.

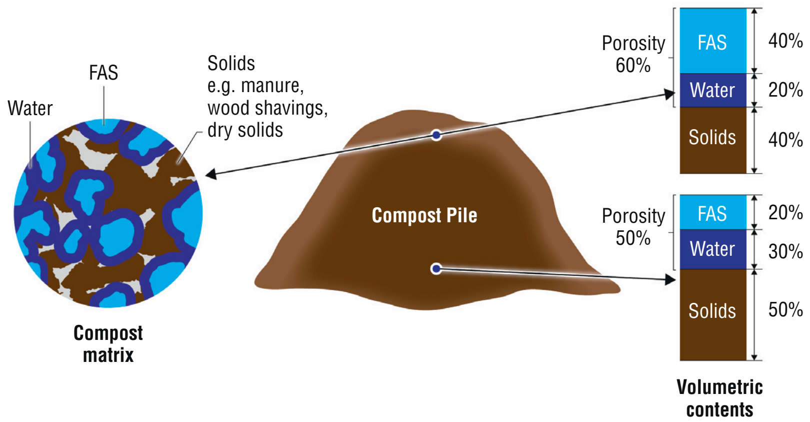

FIGURE 3.17

Relationship of free air space (FAS) to pile depth (hypothetical values).

Adapted from McCartney and Chen (2001).

On the other hand, a feedstock with a great number of small pores may have a high porosity and FAS yet the movement of air is greatly restricted by the small and tortuous pore spaces.

A parameter known as permeability has been used to directly characterize the ease of aeration. Permeability is determined by measuring the pressure required to push air through a sample or section of the composting mass. It is related to pressure drop in a forced aeration system. Researchers have used several methods to measure permeability, such as pycnometers (Ruggieri et al., 2009). However, no instrument has yet emerged for field use. Also, standard recommendations for permeability are lacking. Fortunately, permeability has shown to correlate closely with FAS and bulk density, which are easily determined.

4.7 Bulk density

Bulk density is the mass or weight per unit volume of an accumulation of particulate materials.[2] For instance, bulk density applies to a pile of wood chips while a single wood chip is characterized by particle density or simply density. In the realm of composting, bulk density is commonly expressed in kilograms per cubic meter (kg/m^3) and pounds per cubic yard (tons/yd^3).

[2] Density is technically a measure of *mass* per unit volume. However, when using the US system of units, density is commonly expressed in units of *weight* (lbs., tons) rather than mass (slugs). The quantity given by weight per unit volume is more correctly termed “specific weight.”

Bulk density is perhaps the best single index of how well a mix of feedstocks aerates because it is influenced by several relevant factors—moisture content, porosity, particle size, and the density of the individual particles. It increases with higher moisture and with lower porosity. Therefore, it also reflects the FAS in a composting material. As the straight lines in Fig. 3.18 suggest, bulk density correlates very well with porosity and FAS. In short, bulk density provides an overall indication for the physical and aeration conditions of a composting mass. Furthermore, it is easily measured in the field. Thus, bulk density serves as a good gauge for combining feedstocks and managing the composting process.

As a rule of thumb for most composting feedstocks, the starting bulk density of a feedstock mix should be lower than 700 kg/m^3 (1200 lbs/yd^3), and preferably below 600 kg/m^3 (roughly 1000 lbs/yd^3). Above 600 kg/m^3, aeration becomes increasingly difficult, and beyond 700 kg/m^3 it nearly stops. If the bulk density is very low (below 400 kg/m^3 or about 700 lbs/yd^3), the material may be so porous that heat escapes quickly and the temperatures fail to reach the desired level. Alternatively, the low temperature might be due to abundance slowly decomposing large, woody, or dry

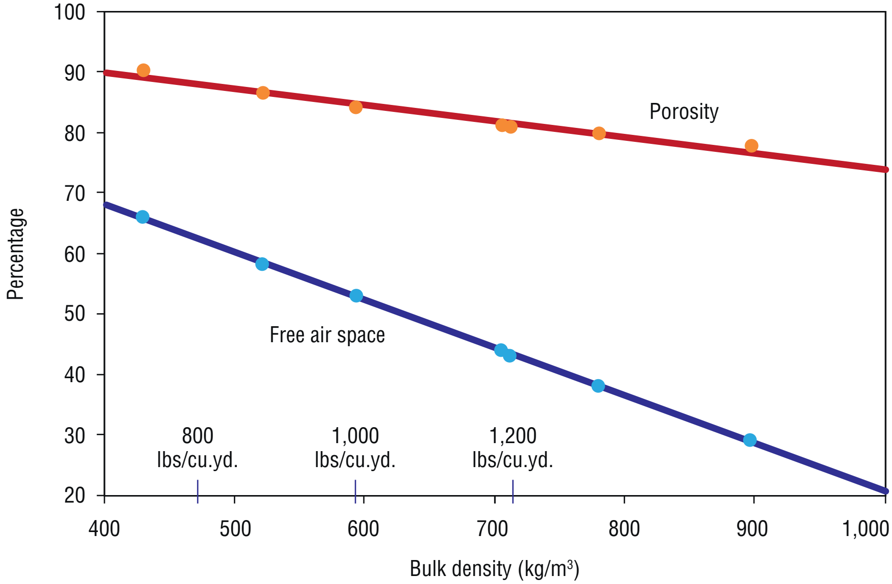

FIGURE 3.18

Correlation of bulk density with free air space (FAS) and porosity for paper-mill deinking sludge.

Adapted from Day and Shaw (2001).

feedstocks responsible for the low bulk density. In either case, this problem is rare and can be overcome by building larger piles.

One problem with using bulk density as a management criterion is that it differs throughout a pile or windrow. Because of compression, bulk density increases from the top to the base of a pile. Thus, bigger (taller) piles tend to have a greater overall bulk density and are more difficult to effectively aerate. When the bulk density of a standing pile is measured, samples must be taken at different depths in the pile or at a depth known to represent the average condition. A large difference in bulk density from top to bottom can be corrected by turning, at least temporarily. Methods used to measure bulk density should account for changes in bulk density as samples are removed from the pile. A standard method for field measurement of bulk density is presented in Chapter 4.

4.8 Pile size

As a pile grows in size, conditions outside the pile exert less influence on conditions inside the pile. A larger pile loses proportionally less heat and moisture to the ambient air, and gains less moisture from precipitation because there is less surface area per unit of pile volume. As a result, these piles are typically warmer than smaller windrows or piles. The path to oxygen-rich ambient air is longer and more tortuous so natural air currents are less effective at supplying the pile with needed oxygen and cooling. Similarly, CO_2, water vapor, and other gases have a more difficult time migrating outward. In addition, as a pile grows in height, the material above presses more weight on the material below. On average, the pile becomes increasingly dense due to compaction. There is a large difference in bulk density between the compacted material at the base of the pile and the loose material near the surface.

Passive aeration is at the mercy of these effects of increasing pile size. It is simply more difficult for a large pile to naturally "breathe" and breathe evenly throughout. Thus, as a pile gains size, it becomes less aerobic throughout, hotter and the composting process slows. Forced aeration or pipes laid beneath the compost can improve conditions in a larger pile, but only up to a certain point. In piles taller than 3 m (10 ft), the densification resulting from settling and compaction tends to cause the air flow to channelize and be less effective. The optimum pile size depends on many factors—the weather, feedstocks, stage of composting, moisture, composting method, etc. Finding the right pile size becomes a balance among these factors plus equipment capabilities and the effective use of the land area. In many cases, the equipment forming the piles determines the maximum height. It is never advisable to drive on a pile, as this causes increased compaction and reduced airflow, thus slowing decomposition. As a general rule, the pile becomes too large when the equipment has to drive onto the pile to reach the top.

4.9 pH

The broad spectrum of microorganisms involved in composting generally allows the process to proceed over the wide pH range typically found in composting feedstocks. The preferred pH is in the range of 6.5–8.0, but the microbial diversity and the natural buffering capacity of the process makes it possible to work within a wider pH range (Box 3.3). Composting may proceed effectively at pH levels between 5.5 and 9. However, it is likely to be slower at 5.5 or 9 than it is at a pH near neutral (pH of 7). Extremely low pH (<5.5) can develop in the first weeks of composting and hinder the process. Also, high pH at the finish can encourage ammonia volatilization and impair compost quality for some uses. While adjusting the pH is rarely necessary, and often inadvisable, there are exceptional cases when additives that raise or lower the pH might be helpful.

Two groups of molecules generally control the pH during composting; organic acids, which are acidic, and ammonium (NH_4^+), which is alkaline. When oxygen is scarce, particularly when composting is just beginning, carbon compounds cannot be completely oxidized to CO_2. They accumulate as organic acids, such as acetate, propionate, butyrate, and others (many of which are odorous). The pH drops, potentially to levels between 4 and 5. Fortunately, these acids oxidize when oxygen is available, allowing the pH to return to neutral pH (Sunberg, 2005; Michel and Reddy, 1998). Ammonium, and subsequently ammonia, form more gradually as urea and proteins decompose. When ammonium is generated, the pH tends to rise to levels between 8 and 9 (i.e., the pKa range of ammonium[3]). This is why the pH of compost is commonly in this range (Box 3.3).

The pH tends to change as decomposition proceeds (Fig. 3.19). The pattern and extent of the pH change varies with the materials and the process conditions. During the early stages of composting, rapidly decomposing feedstocks form organic acids that lower the pH. Usually, the pH recovers within a few days as the organic acids aerobically decompose. If aeration is poor, the organic acids can persist and the pH remains low until enough oxygen becomes available and the acids breakdown. In many cases, depending on the feedstocks, the organic acids decompose almost as quickly as they form and the pH drop is unnoticeable, or it does not occur. In the later stages of composting, the pH either remains stable or slightly rises or slightly falls due to the formation of ammonium and its subsequent conversion to nitrate or protein.

[3] In simple terms, the pKa value indicates how strongly a chemical compound acts as an acid at a given temperature (i.e., donates H^+ ions or protons). Stronger acids have lower pKa values. Without diving into the details of acid/base chemistry, if the pH of a solution is higher than a compound's pKa, the compound donates H^+ ions to the solution, and thus lowers the pH of the solution. This continues until the pH equals the pKa (equilibrium). If the pH is lower than the pKa, the compounds accepts H^+ ions from the solution, raising the solution's pH. Thus, the pKa indicates the level to which a particular compound potentially raises or lowers pH if it is present in high enough concentrations.

Box 3.3 pH by the numbers

pH is a measure of the acidity or alkalinity of a substance. Substances with a pH less than 7 are considered acids. Substances with a pH greater than 7 are alkaline, also called "bases."

Technically, pH is a measure of the concentration of hydrogen ions (H^+) that are present when a substance is in a solution of water. The presence of many H^+ ions create acidic conditions. More specifically, pH is the negative logarithm of the H^+ concentration, written as:

$$pH = -\log[H^+] \tag{3.2}$$

For all but the most extreme acids and bases, H^+ concentrations fall in the range of 1×10^0 (or 1.0) moles per liter) to 1×10^{-14} (or 0.00000000000001) moles per liter. So, all but the most extreme acids and bases have pH values ranging from 0 to 14. A substance with a low pH has a higher concentration of H^+ ions than a substance with a high pH. The negative sign in Eq. (3.2) is to blame this apparent contradiction. Moreover, because pH is based on a logarithm, each whole number change represents a 10-fold different. A pH of 5 is 10 times more acidic than a pH of 6 (i.e., the H^+ concentration is 10 times greater). The alkalinity is 10 times greater at pH 9 versus pH 8.

A pH of 7 is neutral, neither acidic nor alkaline. In pure water, a few molecules disassociate into H^+ and OH- ions while the majority of molecules remain together as H_2O. The "normal" concentration of H^+ ions in pure water is 1×10^{-7}, which is balance with an equal concentration of 1×10^{-7} hydroxide ions (OH^-). Thus, the pH of pure water is 7, neutral.

Anything that increases the H^+ ion concentration in water is an acid and has a pH less than 7. Anything that reduces the H^+ concentration is alkaline. For example, when dissolved in water, an alkaline substance might contribute OH^- ions that combine consume H^+ ions to form water molecules. Alkaline substances have pH values greater than 7. The further that a substance veers from pH 7, the more acidic or alkaline it is. A buffer is a substance that counteracts the effect of acids and bases by either absorbing or releasing H^+ ions. Buffers stabilize pH against changing conditions.

Feedstock mixes that are rich in easily degradable carbohydrates, such as food residuals, can quickly generate an abundance of organic acids that overwhelm the process and drive the pH to excessively low levels (<5.5). As the organic acids accumulate, a sour odor develops in the pile and the escape of volatile organic compounds (VOCs) may lead to odor problems. Research by Sunberg et al. (2005) suggests that keeping the temperatures below 40 C (105 F) affords mesophilic microorganisms the opportunity to degrade the organic acids. Conversely, if temperatures rise above 40 C, the ensuing thermophilic microorganisms are less capable of degrading organic acids, either because of the low pH or the lack of suitable enzymes. In addition, the higher temperatures promote greater volatility of the organic acids and the release of VOCs.

One way to prevent, or correct, this situation is to increase aeration (Fig. 3.20). The effects of the enhanced aeration are to increase the oxygen concentrations to oxidize the organic acids and to better cool the pile and maintain low temperatures that favor mesophilic organisms. With forced aeration, the fan aeration rate can be increased and/or the fan on-time can be extended. With passive aeration, windrows and piles can be made less dense by using more bulking agent, and/or kept smaller until pH rises above 5.5.

Fundamentally, excessively low pH points to an imbalance in the feedstock mix; either the mix contains too high a proportion of quickly degradable feedstocks (e.g., heavy in food residuals), the C:N ratio is too low, and/or the mix lacks FAS and

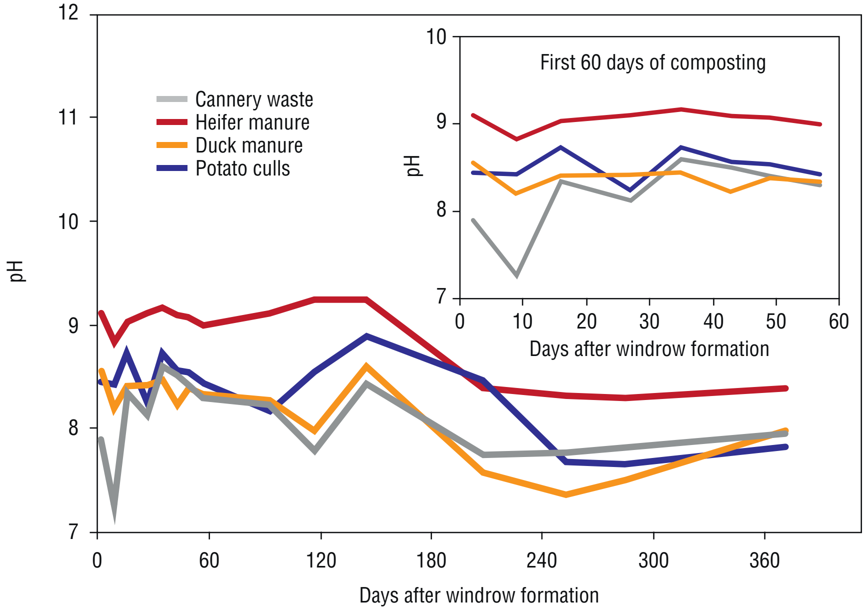

FIGURE 3.19

Example of change in pH over time for four different feedstocks. These particular feedstocks are uncommon, and the pH values are uncharacteristically high. Nevertheless, they are varied, and display different patterns of pH evolution through a long period of composting.

Courtesy of Leslie Cooperband, unpublished data from a University of Wisconsin study of the effects of selected feedstock.

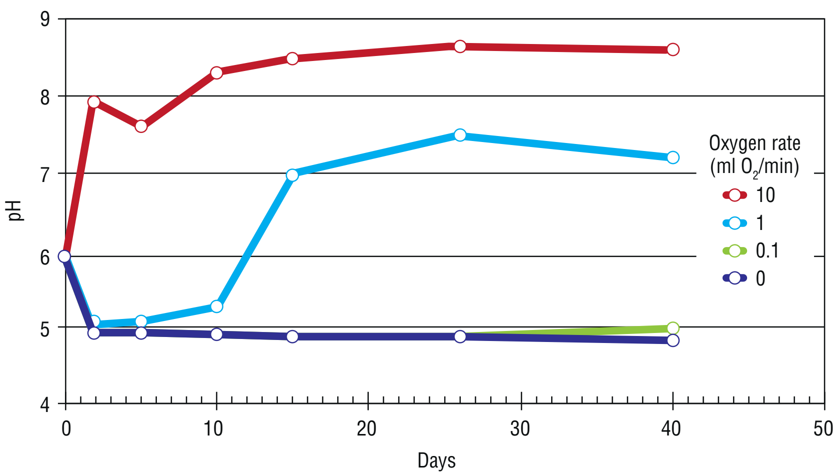

FIGURE 3.20

Effects of oxygen on composting pH. Lower amounts of oxygen result in organic acid formation that reduces compost pH.

Adapted from Michel and Reddy (1998).

structure. Before addressing possible aeration shortcomings, the feedstock recipe should be reexamined. If the feedstocks recipe is not changed, adding lime or wood ash to the feedstocks can immediately raise the low pH. If such additives are used to raise the pH, they should be used in small quantities and should be thoroughly mixed with the other feedstocks.

As composting proceeds, conversion of organic nitrogen to ammonium (NH_4^+) tends to raise the pH. As long as the ammonium persists in the compost, the pH remains elevated. However, over time the ammonium normally converts to gaseous ammonia (NH_3). The ammonia gas either volatilizes or forms new biomass protein. When either reaction occurs, H^+ ions are liberated and the pH decreases, in effect, reversing the pH-elevating effect of ammonium. The pH increase typically occurs a few days into the process, lasts for several weeks, and drops slowly as the concentration of ammonium in the compost declines. Similarly, H^+ ions are released and pH goes down (acidifies) as ammonium is oxidized to form nitrate during the curing phase. These effects are more evident with feedstocks that have high concentrations of nitrogen.

Ammonia volatilization greatly increases at high pH (above 7.5−8.0), which leads to nitrogen losses and reduces the nitrogen content of the finished compost. If desired, ammonia loss can be limited including more acidic feedstocks or adding gypsum to keep the pH below 8.0. Even better, by providing a moderate to high C:N ratio (>30:1), ammonia is conserved as it is converted to microbial protein. Similarly, volatilization of hydrogen sulfide (H_2S) increases as the pH decreases below 7. Maintaining the pH levels near or above 7, limits the emission of this odorous gas.

In the end, composting tends to yield a product with a stable pH that is usually neutral to slightly alkaline, between 7 and 8.5. In many cases, composting results in a slight increase in pH compared to that of the feedstocks. Some feedstocks, like manure, that start with a high pH may produce compost with a slightly lower pH.

4.10 Temperature

Temperature is both a cause and an effect within the composting process. It is a cause in that it influences the rate of biochemical reactions and the organisms involved. It is an effect in that the biological activity produces heat, which in turn changes the temperature. Because of this relationship, temperature is a reliable indicator of the composting process.

Temperature has a profound effect on the composition and activity of microorganisms and the chemical reactions that take place. Within limits, biochemical reactions occur faster at higher temperatures, thus accelerating decomposition. Faster decomposition increases heat production. Higher temperatures increase oxygen demand, sanitize the materials, and promote more evaporation of volatile compounds and water. At lower temperatures, the composting process occurs more slowly. However, nutrients are conserved, organic matter breaks down more slowly, and less odors and volatile compounds are emitted.

As a matter of convenience, scientists have subdivided and given names to the ranges of temperatures within which certain microorganisms thrive. Composting principally takes place within the two ranges known as mesophilic, approximately 20–45°C (68–113°F), and thermophilic, 45–75°C (113–167°F). The range below 20°C (68°F) is called *psychrophilic*. The boundaries between the ranges are not exact, nor important. The relevant point is that different species of microorganism thrive in different temperature regimes.

Composting can take place effectively at mesophilic temperatures, as it typically does in backyard composting piles. In fact, some evidence suggests that, for the same degree of compost maturity, more carbon and nitrogen are conserved when composting takes place under mesophilic temperatures compared to thermophilic (Adler and Sikora, 2005). Mesophilic microorganisms are better able to perform certain biochemical tasks, like degrading organic acids and converting ammonia to nitrate.

Nevertheless, large-scale composting is generally managed with the goal of attaining and maintaining temperatures in the thermophilic range for a prolonged time period. In addition to faster decomposition, thermophilic temperatures are desirable because they destroy more pathogens, weed seeds and fly larvae present in the composting materials than mesophilic temperatures alone. Research has shown that human and animal pathogens are reduced by more than 99.999% after three days of composting at 55°C (131°F). This temperature should destroy most plant pathogens as well. Therefore, various national, state, and provincial composting regulations set the critical temperature for killing human pathogens during composting to be 55°C (131°F) or higher, when maintained for a specified time period. This pathogen-destroying process is generally termed "sanitization." In the United States, temperature/time sanitization requirements are known by the acronym PFRP (Process to Further Reduce Pathogens) (Box 3.4).

An effective temperature target for destroying weed seeds is 60°C (140°F). The critical temperature depends on the weed species, the time of exposure, and moisture (dry conditions tend to protect seeds). Most weed seeds cannot survive the 55°C threshold level for even a few hours. The vast majority of seeds are destroyed within an hour between 60°C and 70°C (158°F) (Dahlquist et al., 2007). However, with a few especially hardy weed species, a percentage of seeds can remain viable even after weeks of composting at these high temperatures.

60°C (140°F) is often cited as the optimal composting temperature for microbial diversity and general rate of decomposition. However, the optimal temperature is likely a moving target that changes with the phase of composting, specific feedstocks, and desired final product qualities. For example, high temperatures, near 75°C (167°F), have been reported to enhance the decomposition of feedstocks of fats, oils, or waxes. Experience and research indicate that temperatures in the range of 50–70°C range (roughly 120 to 160°F) generally work well. As a rule of thumb, to speed the process and promote decomposition and evaporation, one should

Box 3.4 Sanitization and the "Process to Further Reduce Pathogens (PFRP)"

A key function of composting is "sanitization" (aka "pasteurization")—producing compost that is effectively devoid of pathogens, organisms that cause disease. Human pathogens are of greatest concern, but the destruction of animal and plant pathogens is also important. The goal is to diminish pathogen numbers to a level small enough that the risk of passing on a disease is very low, *acceptably* very low. Acceptably low results might require the destruction 99.9% to 99.999% of a particular pathogen.

Composting kills pathogens primarily with heat. The harsh environment of a composting pile, including competition and predation by other organisms, also destroy pathogens, but high temperature is the most certain and effective killer. The US EPA considers 55°C (131°F) the threshold temperature for killing pathogens via composting. Other countries set the bar a bit higher, at 60°C, and even up to 65°C (149°F) for certain feedstocks up to 65°C (149°F). However, simply reaching the lethal temperature threshold is not enough. To have its desired effect, lethal temperatures must be attained throughout the composting mass, and maintained for a sufficient length of time. Therefore, composting regulations that govern sanitization typically specify a minimum temperature *and* a minimum time of exposure at that temperature. Some regulations also specify a minimum moisture content to maintain during the sanitization period because dry materials interfere with heat transfer. Regulations also address the likelihood that composting piles and windrows are not uniformly hot; cool spots can endure at the margins.

Different countries, provinces, and states have varying rules and regulations regarding how composters accomplish and document sanitization. Although the specific requirements vary, the temperature/time model is almost universally followed. The reader should research the specific regulations in his/her own political jurisdictions.

Sanitization requirements for composting are epitomized by the set of rules that underlies regulations in the United States. These rules are known by the acronym PFRP. The PFPR rules were established by the US EPA as one of several options for the treatment of wastewater biosolids. In actuality, composting is only one of the "processes" specified to "further reduce" pathogens. However, the composting part of these rules have since become the basis for regulations and/or practices regarding composting of many feedstocks. When composters say that they are meeting PFRP, they mean that they are meeting the requirements for composting under the broader PFRP rules.

The US EPA's PFRP criteria depend on the method of composting.

- For composting by either the aerated static pile or an in-vessel methods, the temperature must be maintained at or above 55°C or for three days.
- For composting by the turned windrow method, the temperature must be maintained at 55°C or higher for 15 days or longer. Also, the windrow must be turned a minimum of five times during the period that the temperature remains at 55°C or higher.

Turned windrows merit a longer time is because they tend to be smaller in size. A large portion of the material is at or near the exposed exterior surface and remains cool even if the interior is hot. Turning the windrow five times ensures that all of the material in the windrow spends time within the hot core. In contrast, aerated static piles and in-vessel systems are considered to be large enough or well-insulated enough to experience high temperatures throughout.

In the United States, implementation and oversight of the PFRP rules are the responsibility of individual states. State environmental agencies can impose stricter criteria and additional requirements, such as minimum temperature monitoring and record keeping provisions. On a national level, the PFRP rules apply only to biosolids and septage. In many states, composters who do not handle these feedstocks are not compelled to meet PFRP rules, though it is a good idea to do so anyway. However, most states also require PFRP compliance with higher-risk feedstocks like municipal solid wastes and postconsumer food waste. A few states have expanded the PFRP burden to nearly all feedstocks, including yard trimmings. Fortunately, it is easy for most composting piles and windrows to reach 55°C, even 65°C, and stay at that level for several weeks.

operate at the higher end of this temperature range. To slow things down, conserve nutrients and limit odors, one should maintain lower temperatures, that is, *after* the compost is sanitized of pathogens and weed seeds, if and as necessary.

The temperatures of a compost pile are determined by both the amount of heat generated *and* the amount of heat lost to the surrounding environment. When heat generation exceeds heat loss, the temperatures increase. When heat loss prevails, the temperatures decline. Organic matter decomposition by microorganisms inherently releases large amounts of energy as heat. The self-insulating qualities of the composting materials lead to an accumulation of heat, which initially raises the temperature. At the same time, the materials continuously lose heat as water evaporates and as air movement carries away the water vapor and other warm gases. Aeration accelerates heat loss and, therefore, is used to maintain temperatures in the desired range. Cold weather and small piles also promote heat loss.

Heat accumulation can push temperatures well above 60°C (140°F). When this occurs, microorganisms begin to suffer the effects of high temperature, and the composting process slows. The temperature can continue to rise above 70°C (about 160°F) because of heat generated by ongoing microbial activity and the insulating qualities of the composting materials. At temperatures approaching 80°C (175°F), many microorganisms die or become dormant (e.g., form heat-resistant spores). The process effectively stops and does not recover until the population of microorganisms recovers. To prevent this situation, temperature should be monitored. When the temperature approaches 160°F (71°C), heat loss should be accelerated by increasing aeration or by reducing pile size. Turning does not reliably lower temperatures. If a pile is set back by high temperature, the recovery may be quickened by remixing the pile, either with the parts of the pile that are not as hot, like the outer edges, or, in extreme cases, with material from other more active batches.

Maintaining adequate moisture is a key to limiting temperature rises in a pile. Most of the heat loss in composting occurs by the evaporation of water. Thus, moisture serves as a temperature buffer. The pile should not be allowed to dry below 40% moisture. Very low moisture, below 40%, increases the chance of damaging high temperatures as well as spontaneous combustion (Chapter 12).

4.11 Time

The length of time required to transform raw feedstocks into usable compost depends upon many factors including the feedstocks themselves, temperature, moisture, frequency of turning, effectiveness of aeration, and the intended use of the compost. Proper moisture content, a suitably low C:N ratio, regular agitation plus adequate aeration ensure the shortest possible composting period. Conditions which slow the process include lack of moisture, excessive moisture, a high C:N ratio, insufficient aeration, large particles, and a high percentage of feedstocks that are resistant to biodegradation, such as woody materials. The required composting period also depends on the intended use of the compost. It can be shortened if the compost does not need to be fully mature. For instance, if the compost is to be applied to cropland well before the growing season, it can cure in the field.

In general, the entire decomposition and stabilization of materials, from feedstock to usable compost product, is typically accomplished in three months to a year. Some compost producers prefer to manipulate the process as little possible and wait as long as two years to harvest compost. Under tightly controlled conditions, it is possible to produce useable compost within one month but a minimum period of 10 weeks is more reasonable. Typical composting times for several common applications are given in Table 3.3.

Although some in-vessel composting systems may claim less than one week to produce compost, an additional composting phase, lasting four to eight weeks, is required before the compost is suitable for general use. Also, a given process might achieve stabilization quickly by drying the materials to a low moisture content,

Table 3.3 Typical composting times for selected methods and feedstocks.

Composting method	Example feedstocks	Primary composting period		Curing period
		Range	Typical	
Passive composting (little or no turning)[a]	Leaves	1½–3 years	1½ years	–
	Well-bedded manure	6 months to 2 years	1 year	–
Windrow—infrequent turning[b]	Leaves	6 months to 1 year	9 months	4 months
	Manure + amendments[e]	4–8 months	6 months	1–2 months
Windrow –frequent turning[c]	Manure, food scraps + amendments	1–4 months	2 months	1–2 months
Passively aerated windrow	Well-bedded manure	10–12 weeks	–	1–2 months
	Fish scraps + peat moss	8–10 weeks	–	1–2 months
Aerated static pile	Biosolids, manure food scraps + amendments	3–5 weeks	1 month	1–2 months
Agitated bed	Biosolids, manure food scraps + amendments	2–4 weeks	3 weeks	1–2 months
Rotating drums	Biosolids + MSW manures	3–8 days	3 days	2 months[d]

[a] *Little or no turning = static piles that may be moved with a bucket loader once or twice.*
[b] *Infrequent turner—typified by turning with a bucket loader or excavator every other month on average.*
[c] *Frequent turner—typified by turning with a windrow turner every 2–4 weeks on average.*
[d] *These methods involve a second stage of composting in windrows or aerated piles.*
[e] *Amendments—feedstocks used to balance moisture, bulk density, or other parameters, e.g., wood chips added to biosolids or yard debris added to food scraps.*

which inhibits biological activity. This is fine if the end use for the compost does not dictate biologically stable compost. Partially stabilized compost, however, is not suitable for most uses. It is also important to recognize that as the dried material regains moisture, biological activity resumes. Odors, pathogen regrowth, and other problems can then develop if the material is not stabilized.

5. Curing

Curing is an extremely important but too-often neglected stage of composting during which compost matures. Curing occurs at lower, mesophilic temperatures. The oxygen consumption, heat generation, and moisture evaporation are much lower than in the active composting stage. There is no precise point at which curing should begin (or end). Conceivably, the curing stage begins when a windrow or pile no longer reheats after turning. With forced aeration, curing begins after the pile temperature shows a steady decrease and approaches mesophilic levels (40°C or 105°F), and air is no longer required for cooling, assuming there is adequate moisture.

Curing furthers the aerobic decomposition of resistant compounds, organic acids, large particles, and clumps of material that remain after active composting. Some fungi and actinomycetes that can breakdown cellulosic compounds are only active in the mesophilic temperature regimes of curing. As a result, the C:N ratio decreases, the exchange capacity increases, and the concentration of humic compounds increase. Some desired changes take place only at low temperatures or within well-decomposed organic matter, which is not present during thermophilic composting. One example is nitrification, or the conversion of ammonia to nitrate-nitrogen. Nitrification only becomes noticeable during the curing stage. Another is the recolonization of the pile by soil organisms, which can give the compost disease-suppressing qualities. The development of humus-like compounds is also believed to occur more readily at these conditions.

The importance of curing, and its duration, increases if the active composting stage is either shortened or poorly managed. A long curing period provides a safety net that helps to overcome the shortcomings of the composting method and also reduces the chance that immature compost will be used. Intermediary compounds produced during thermophilic decomposition, some of which are phytotoxic,[4] are fully broken-down during curing. Immature compost continues to consume oxygen and thereby reduces the availability of oxygen to the plant roots. It can also contain high levels of organic acids and ammonium, a high C:N ratio, and other characteristics which can be damaging when the compost is used for certain horticultural or agricultural applications. In principle, the duration of curing should be determined

[4] "Phytotoxic" means harmful to plants.

by the desired maturity level of the compost. The prevailing rule of thumb recommends a minimum curing time of one month.

Because curing continues the aerobic decomposition process, adequate aeration remains a necessity. The continued need for oxygen limits the size and moisture content of the curing piles. Compost, or pockets of compost, that becomes anaerobic within the curing piles develop some of the same detrimental qualities found in immature compost. However, because curing is less biologically active than the thermophilic phase, oxygen demand is much less, so curing piles can be larger than their predecessors without becoming anaerobic. If anaerobic conditions do occur in curing piles, the resulting anaerobic products can be degraded relatively quickly when the cured compost is exposed to air. It is a good practice to move compost to smaller curing or storage piles, and allow them to aerate, before using or selling the compost.

Shaffer (2010) presents an excellent explanation of the importance of curing and its role in producing compost that is fit for its intended use.

6. When is it done?

The question of when the compost process is finished vexes many novice composters. The process is dynamic and complex. As noted above, temperature alone is not sufficient because a drop in temperature may only indicate the transition from the thermophilic phase to curing, or it may indicate one of the key parameters, such as oxygen or moisture, has become limiting. Part of the challenge is that the answer depends on the intended use for the compost. Some applications require a more-finished compost; others can use immature compost. Two terms used to describe a compost's state of completion are stability and maturity (see Chapter 15).

Stability refers to the biological activity of the compost. As the available food for microbial growth and development diminishes, populations decline. This condition is accompanied by a decrease in respiration, reducing how much oxygen is used and carbon dioxide is given off. Either of these gases can be used as a measure of stability. However, respiration can also decrease because other growth conditions become unfavorable. For example, a pile that gets too dry may appear stable as measured by CO_2 release, but will become more active when remoistened. Using this compost could lead to nitrogen immobilization or oxygen depletion in the soil that can inhibit or damage plant growth.

Maturity is a related but more complex and less well-defined concept that generally describes the degree of doneness of compost. Since rapidly decomposing organic matter produces compounds that can be phytotoxic, maturity is typically interpreted as the ability of compost to support plant growth. Mature compost presents little risk of plant damage in almost any situation. Immature composts may damage some plants in some situations. Because of the problems mentioned above with stability, mature compost is stable but stable compost may not be mature. Moreover, it is still possible for a mature compost to cause harm to some plants for reasons other than the degree of decomposition, such as a high ammonia concentration or the presence of persistent herbicides.

Table 3.4 Characteristics of compost maturity levels.

Maturity level	Traits	End use examples
Immature	May produce odors Significant potential to inhibit plant growth Significant potential to impact nitrogen availability in soil	Amend fallow soil Add organic matter to depleted soils Feedstock for compost Mulch for weed control in orchards
Mature	Unlikely to produce odors Limited potential to inhibit plant growth Minimal impact on soil nitrogen	General field use Vineyards, row crops Garden or landscape bed amendment
Very mature	No malodors No potential to inhibit plant growth	Container plant mixes Turfgrass topdressing

Adapted from CalRecycle. 2003. The Importance of Compost Maturity. CIWMB Pub. #443-03-007. https://www2.calrecycle.ca.gov.

No single test parameter is sufficient to measure maturity, though many have been proposed (Chapter 15). Most tests for maturity include a measure of stability. The surest way to tell if compost has reached adequate maturity is to grow plants in it. This is called a bioassay, a procedure that follows testing protocols that include optimizing moisture, seed selection, lighting, and other growth factors, and compares the results to a known control. As noted, not all uses require mature compost (Table 3.4).

7. Composting microbiology[5]

The composting process occurs through the work of microorganisms, mainly bacteria and fungi. A single teaspoon of active compost can contain 10 billion bacteria. Tending the compost pile has been called the "care and feeding of the microherd." Just as a farmer provides the right environment (food, water, and shelter) for a herd of livestock to thrive, so a composter provides the right conditions for the microbial "herd" to do their work breaking down and stabilizing the feedstocks.

The microorganisms that are at work in a compost pile are extremely diverse, with perhaps 1000's of species at work at various times in the process. Some microbes are fairly specialized in the food and conditions to which they are adapted while others can use many different substrates and survive under a broad range of

[5] The book, *Microbes at Work: From Wastes to Resources* (Insam et al., 2010), presents much more information about the types and functions of microorganisms in composting.

conditions. The compost pile usually has a variety of local environments that change as the process advances, so the mix of microbial communities is always shifting.

Bacteria and fungi are the primary decomposing organisms (Figs. 3.21—3.23). Bacteria are by far the most diverse organisms on earth having evolved over four billion years. They are small (0.5 to 3 microns), simple single-celled organisms that exist in a wide variety of forms. They are often subdivided based on their genetic sequences or into groups along functional lines, including aerobes, anaerobes, actinomycetes, and nitrogen fixers. Fungi are less diverse and include yeasts and molds, some of which produce mushrooms. They are larger than bacteria (10 to 50 microns). Yeasts are unicellular. Molds form long multicellular filaments called mycelia. As a group, fungi are more tolerant of dry conditions and lower nitrogen levels but less tolerant of anaerobic situations and high temperatures. Actinomycetes are a type of bacteria that form multicellular filaments like fungal mycelia. These networks of cells allow both actinomycetes and molds to "forage" farther for nutrients than single-celled bacteria can access from their surroundings. However, turning and other forms of agitation can disrupt and distribute the networks of mycelia and filaments of actinomycetes.

Bacteria clearly dominate the composting realm. Their numbers are typically about 100 times greater than fungi. Bacteria flourish particularly well when the conditions are good for decomposition—abundant moisture, easily degradable feedstocks, and thermophilic temperatures. Overall numbers are highest at the beginning of the process and decline as organic matter becomes more stable. Fungi, and actinomycetes, gain some ground near the end of the process when the tougher organic compounds remain.

New molecular techniques in microbial identification and analysis have greatly increased our knowledge of the microbiology of composting. For example, Fig. 3.24 shows the relative numbers of bacterial and fungal classes found in 10 different compost products by sequencing conserved parts of the DNA that makes up their

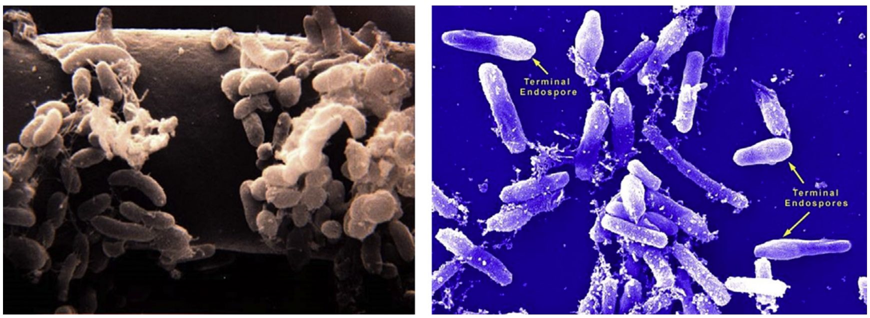

FIGURE 3.21

Thermophilic *Bacilli*, the genus of bacteria most commonly isolated by culturing from active thermophilic composts. Note the characteristic spores.

Permission granted by Fred Michel and the USCC.

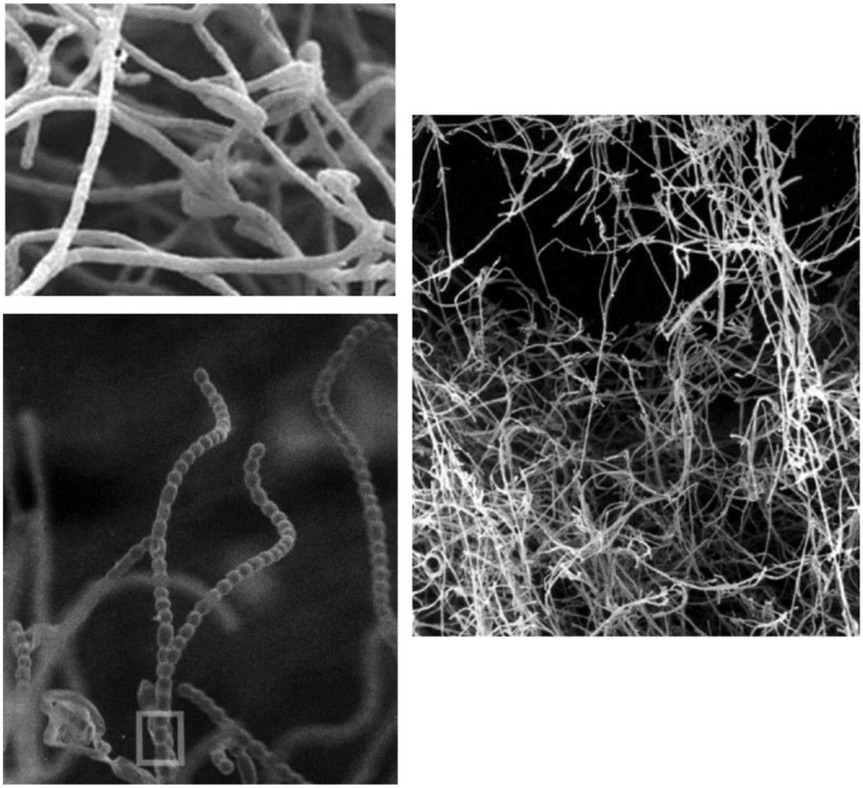

FIGURE 3.22

Actinomycetes—a type of bacteria found in mature composts that forms a network of threads or mycelia.

Courtesy of Fred Michel and the USCC.

genomes and comparing the sequences to databases of similar genes (Michel, 2020). Genome sequencing has greatly expanded and simplified our ability to identify microorganisms in composts compared to the microbial culturing techniques used in the past. However culturing and other methods can provide complimentary information about the specific capabilities and processes that microorganisms carry out.

These molecular methods of identification have revealed that the diversity of microorganisms at both the phylum and species level is significantly greater than previously understood. This diversity is what gives the composting process the ability to adapt to changing conditions. It also holds out the promise of discovering strains of microorganisms that will be particularly suited to advancing work in disease control, bioremediation, enzyme discovery, and other biotechnologies.

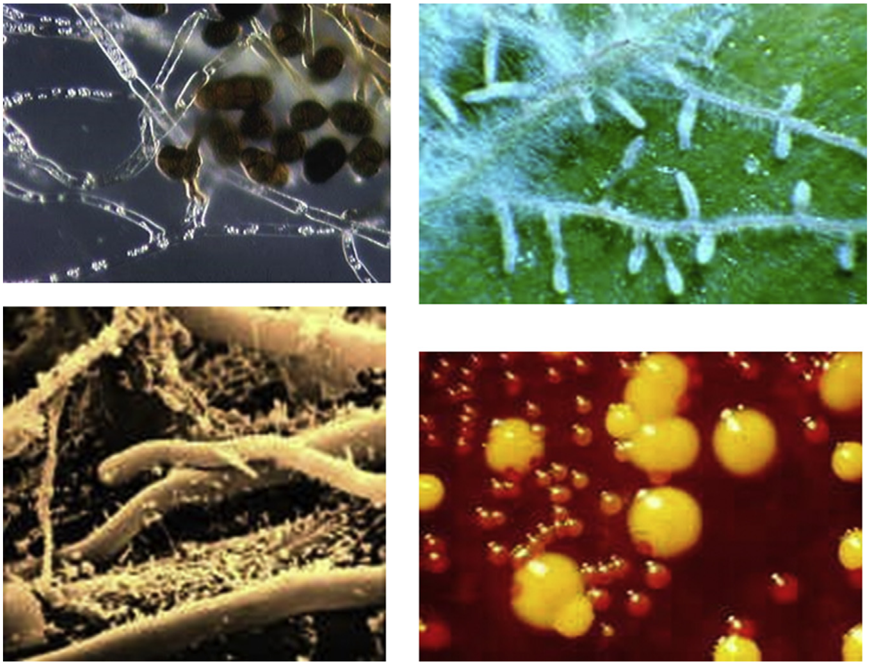

FIGURE 3.23

Fungi—molds and yeasts (bottom right photo). Bottom photo is a white rot fungus capable of lignin degradation. Fungi are more temperature sensitive than bacteria.

Courtesy of Fred Michel and the USCC.

In addition to bacteria and fungi, other organisms participate in the composting process but to a much lesser extent and primarily at the later stages. They are more prominent in backyard composting situations and other applications where temperatures are largely mesophilic. These organisms include protozoa, algae, nematodes, and macroorganisms including worms, mites, millipedes, insects, and similar creatures (CWMI, 1996). Some of these organisms, like protozoa, prey on bacteria and fungi, helping to incorporate the biomass into the compost. Although they do not play a large role, algae can colonize moist surfaces of pile, use nutrients from the pile, and add biomass through photosynthesis. Larger organisms, such as worms and insects, produce both biological and physical degradation when temperatures remain at mesophilic levels, mostly at the end of the process. The high temperatures attained during the early and middle phases of composting are lethal to these organisms. Earthworms, fly larvae, and some species of beetles are able to transform raw feedstocks into a valuable compost-like product, but these processes are different from conventional composting and occur at mesophilic temperatures. For the most part, composting relies on the services of microorganisms—principally bacteria and fungi—to manufacture compost.

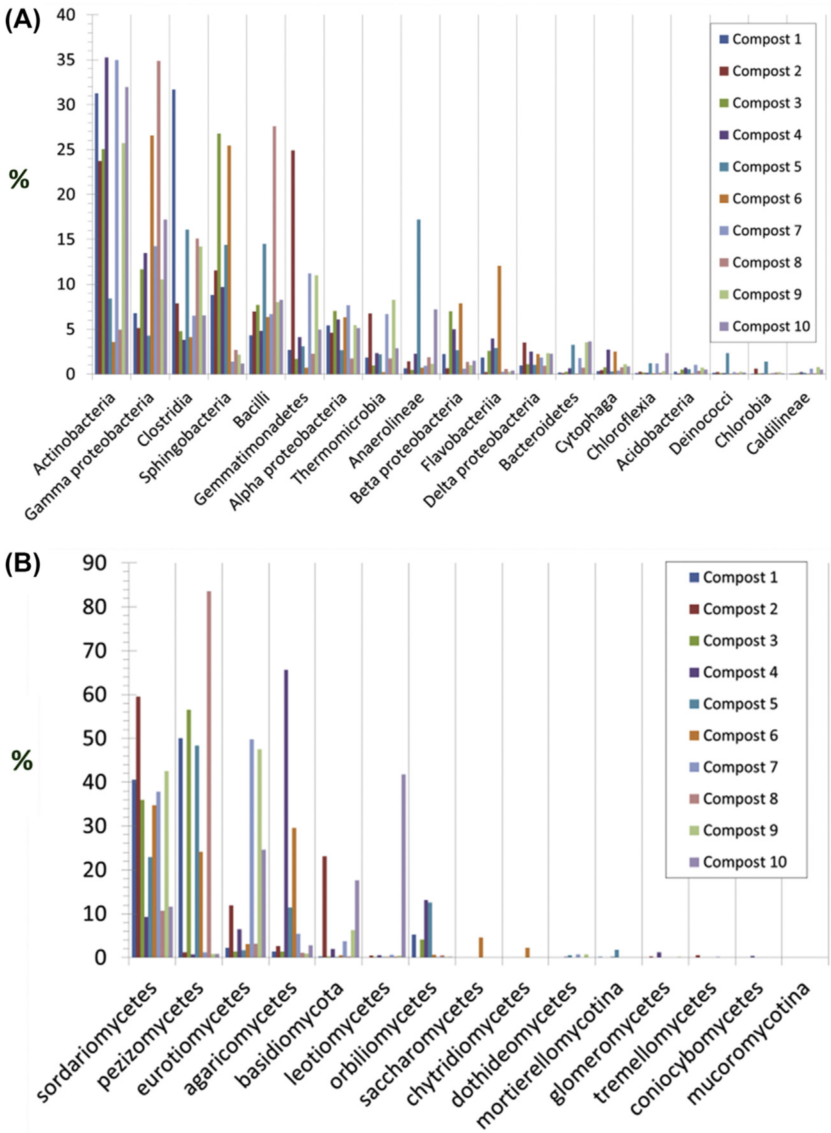

FIGURE 3.24

Prominent classes, of bacteria (A) and fungi (B) and their relative abundance in 10 different mature composts, identified using ribosomal 16S DNA and intergenic spacer region (ITS) amplification and sequencing.

Permission granted by Fred Michel (Michel, 2020).

7.1 Microbial functions

There are a number of important processes that microorganisms perform in the compost process. These include:

- Decomposition: breakdown of plant and animal remains into simpler parts,
- Mineralization: conversion of organic compounds into inorganic ions (e.g., nitrate, phosphate, ammonium, carbon dioxide, hydrogen sulfide, etc.),
- Immobilization: incorporation of water-soluble inorganic and organic molecules into more complex molecules and microbial cells,
- Humification: conversion of lignin, proteins, and other organic fractions into humic substances (large molecules resistant to further decay).

As the composting process proceeds, there is a succession of microorganisms based on food availability and temperature. When the pile is first formed, simple compounds such as proteins, sugars, and starches are consumed by mesophilic bacteria. Heat generated in the breakdown process is trapped in the pile and the temperature rises, allowing thermophilic bacteria to increase at the expense of the mesophiles. The thermophiles go to work on the proteins and fats, which are also readily degradable. This period is the time of greatest oxygen demand. As oxygen levels decrease, or are locally depleted, facultative bacteria switch from aerobic to anaerobic respiration. Those species that require oxygen die or become dormant while the anaerobes increase. If and when oxygen becomes more available, the reverse occurs.

Meanwhile, other thermophilic bacteria work on more resistant compounds, such as hemicellulose, pectin, cellulose, and chitin. Cellulosic compounds are the building blocks of plants; chitin is a structural component in the cells of fungi, insects, and crustaceans. Finally, as the proteins and other readily degraded food sources are exhausted and temperatures drop, the fungal activity increases relative to the bacteria. Fungi work with bacteria, especially actinomycetes, to complete the breakdown of cellulose and begin to work on the most resistant compound, lignin. This stage is also when ammonia is converted to nitrate (nitrification) and free-living (as opposed to symbiotic) nitrogen-fixing bacteria can proliferate, as readily available nitrogen compounds are depleted.

The concentration of the various classes of microorganisms in mature compost depends on the initial feedstocks and the management of the process, and can vary by many orders of magnitude.

7.2 Microbial sources

The microorganisms needed for composting are found throughout the natural environment. They are present as spores or dormant cells on virtually all the feedstocks, as well as in the soil and air. Some manufacturers and some experienced composters promote the use of an inoculant at the start of composting, adding specific bacteria and fungi that help the process proceed faster or with fewer odors or to produce compost with specific qualities. There is little scientific evidence to support this practice, as these additions are usually overwhelmed by the naturally occurring microorganisms. Inoculation may be most effective for feedstocks that have been treated to reduce their microbial numbers; for example, cooked or otherwise preserved foods. In any case, the best inoculant may be a small amount of finished or immature compost made from similar feedstocks. Unlike an inoculant made from a standard recipe, this compost already contains organisms specifically adapted to the conditions and feedstocks of the composting system at hand.

There has been some research to support the use of certain inoculants during the curing phase, particularly to impart a specific disease-suppressive ability to the compost. However, this requires very tight control and generally has not proven to be as consistent as needed to be economically viable. See Chapter 14 for more information on using compost for disease suppression.

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