Biological, Chemical, and Physical Processes of Composting

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CONTENTS

I. INTRODUCTION

The composting process was known and used by man since he changed from being a hunter to a gatherer. As our ancestors started to grow crops they observed that they grew better near rotting piles of vegetation and manure than elsewhere. This finding alone, although a casual observation, was scientific in nature and the discovery was not overlooked but passed on from generation to generation. Clay tablets unearthed in the Mesopotamian Valley dating back to the Akkadian Empire, 1000 years before Moses, attest to the use of compost in agriculture. However, it has only been since the Second World War that any major efforts have been made to focus on the scientific processes occurring during the actual composting period. Prior to the last few decades composting was mostly left to chance. However, today it is a big business and large private and public composting operations are now being accepted as the most environmentally acceptable way to divert about 50% of the waste destined for landfills. The development of these large composting operations has been stimulated by local and federal regulations prohibiting the disposal of yard wastes or other biodegradable materials in landfills.

The number of composting facilities, both aerobic and anaerobic, grows every year. Since 1985, the journal *Biocycle* has listed annually the number and type of composting facilities in the U.S. In 1998 there was a total of 250 food waste composting projects with 187 in operation, 37 pilots, and 26 in development in the U.S. (Goldstein et al., 1998). Biosolids composting facilities have decreased from a high of 338 in 1996 to 321 in 1998, with 274 operational (Goldstein and Block, 1999). Solid waste composting got a boost in 1998 with 18 municipal solid waste (MSW) composting facilities operating and 2 more scheduled to open in 1999 (Glenn, 1998). Anaerobic facilities are closed systems and so have the added advantage over the aerobic systems of controlling odors and capturing the gaseous methane that can be used for fuel, but they can be more expensive.

Naylor (1996) observed that without the natural decomposition of organic wastes that has been going on for eons we would be miles deep in dead organic matter. Dindal's Food Web of the Compost Pile (Dindal, 1978) can be applied to the first stage of the natural decomposition of all types of organic wastes (Figure 2.1).

First level consumers at the compost restaurant are the microorganisms such as bacteria, actinomycetes, and fungi. These species are the true decomposers. They attack, feed on, and digest the organic wastes before they themselves are consumed by the second level organisms, such as the protozoa and beetle mites. The third level
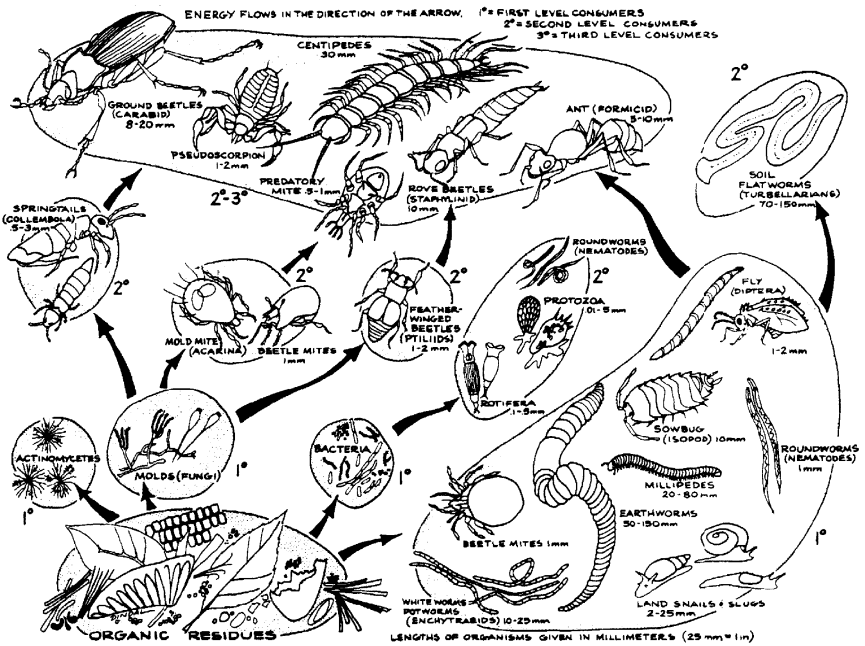
Figure 2.1 Food web of the compost pile. (From Dindal, D. L. 1978. Soil organisms and stabilizing wastes. *Compost Science/Land Utilization* 19(8): 8–11. With permission. www.jgpress.com)

consumers, e.g., centipedes and ground beetles, then prey on the second level consumers and on themselves. It is a very efficient system with the various levels of microflora being essential to the successful functioning of the composting process. The microflora dominate in most commercial (large-scale) operations. This chapter reviews the biological, chemical, and physical changes that occur during the actual composting process.

II. SPECIFIC BIOPROCESSES IN COMPOSTING

Composting is a mass of interdependent biological processes carried out by a myriad of microorganisms essential for the decomposition of organic matter. Most systems are aerobic, meaning the microorganisms require oxygen (O_2). The overall biochemical equation can be written:

$$\text{Organic Matter} + O_2 + \text{AEROBIC BACTERIA} =>$$

$$CO_2 + NH_3 + \text{Products} + \text{ENERGY}$$

For anaerobic systems, oxygen is absent and the overall biochemical equation takes a different form:

$$\text{Organic Matter + ANAEROBIC BACTERIA =>}$$

$$CO_2 + NH_3 + \text{Products} + \text{ENERGY} + H_2S + CH_4$$
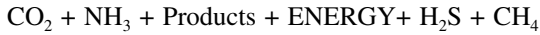
The energy produced in an aerobic system is mainly in the form of low-grade heat. The self-heating, which is produced by the microbial oxidation of carbon (C), occurs spontaneously when the mass of the organic wastes is sufficient for insulation (Baader and Mathews, 1991; Finstein, 1992; Finstein and Morris, 1975). Although the last few years have seen a steady increase in commercial anaerobic composting facilities, aerobic composting operations still dominate.
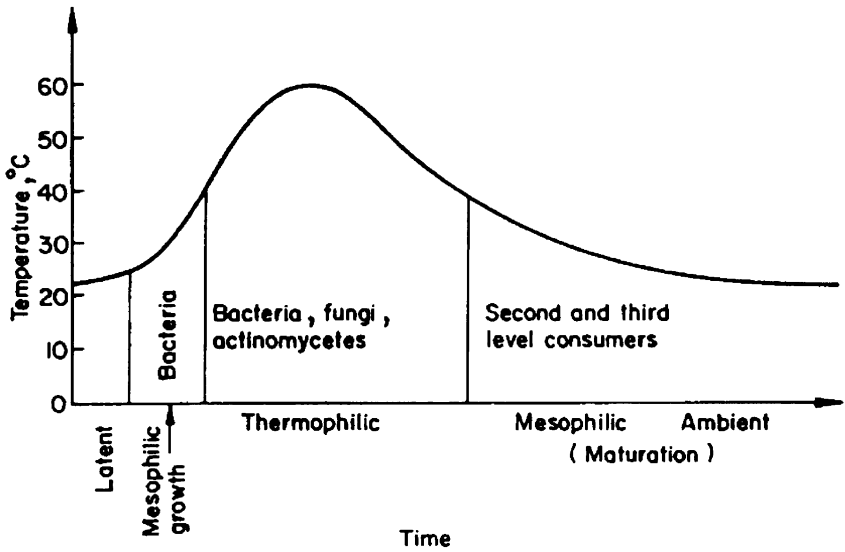
A. Temperature Cycle

Temperature is the primary factor affecting microbial activity in composting (Epstein, 1997; McKinley and Vestal, 1985; McKinley et al., 1985). The microorganisms that populate a composting system are temperature dependent and can fall into three classes (Brock et al., 1984; Krueger et al., 1973; Tchobanoglous et al., 1993):

Cryophiles or psychrophiles	0–25°C
Mesophiles	25–45°C
Thermophiles	>45°C

Cryophiles are rarely found in composting, but winter composting does take place successfully in Canada and the northern U.S., where ambient temperatures range from –27 to 15°C (Brouillette et al., 1996; Fernandes and Sartaj, 1997; Lynch and Cherry, 1996). The organisms that predominate in commercial composting systems are mainly mesophiles and thermophiles each contributing at different times during the composting cycle. Temperature is also a good indicator of the various stages of the composting process. Frequently, the temperature profile of the composting process is shown as a simple curve such as Figure 2.2 (Burford, 1994; Polprasert, 1989). However, in many cases a more complex temperature profile is obtained as shown in Figure 2.3 (Day et al., 1998; Liao et al., 1996; Lynch and Cherry, 1996; Papadimitriou and Balis, 1996; Sikora et al., 1983; Wiley et al., 1955). In this case after the first increase in temperature, the temperature drops a few degrees before continuing to increase to 60°C or more. The temperature then plateaus briefly at 65 to 70°C and then starts to decrease slowly down through a second mesophilic phase to ambient temperature.

Based on microbial activity, the composting process can be divided into four different stages (Figures 2.2 and 2.3). The first stage is the mesophilic stage, where the predominant microbes are the mesophilic bacteria. The abundance of substrate at this time ensures that the microorganisms are very active, leading to the generation of large quantities of metabolic heat energy, which causes the temperature of the compost pile to increase. According to Burford (1994), Finstein (1992), and McKinley et al. (1985), the microbial activity in the 35 to 45°C range is prodigious (see Table 2.1). As the temperature rises past 45°C, conditions are less favorable for

Figure 2.2 Patterns of temperature and microbial growth in compost piles. (From Polprasert, C. 1989. *Organic Waste Recycling*. John Wiley & Sons Ltd., Chichester, United Kingdom, p. 67. With permission.)
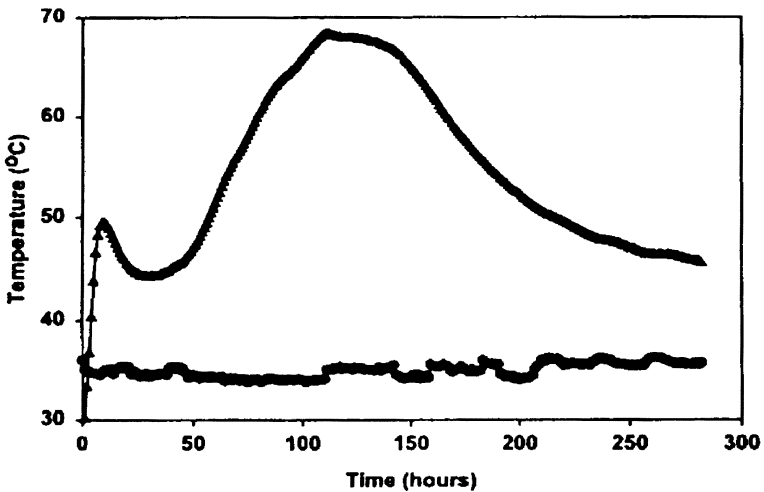
Figure 2.3 Temperatures recorded by the middle thermocouple (▲) in the laboratory composter as a function of time for a CORCAN test sample on day 0. Room temperature in the composting laboratory shown (●). (From Day, M., M. Krzymien, K. Shaw, L. Zaremba, W.R. Wilson, C. Botden and B. Thomas. 1998. An investigation of the chemical and physical changes occuring during commercial composting. *Compost Science & Utilization* 6(2):44-66. With permission. www.jgpress.com)

Table 2.1 Microfloral Population During Aerobic Composting[z]

Microbe	Mesophilic Initial Temp. <40°C	Thermophilic 40-70°C	Mesophilic 70°C to Cooler	Number of Species Identified
Bacteria				
Mesophilic	10^8	10^6	10^{11}	6
Thermophilic	10^4	10^9	10^7	1
Actinomyces				
Thermophilic	10^4	10^8	10^5	14
Fungi[y]				
Mesophilic	10^6	10^3	10^5	18
Thermophilic	10^3	10^7	10^6	16

Note: Number of organisms are per g of compost.

[z] Composting substrate not stated but thought to be garden-type material composted with little mechanical agitation.

[y] Actual number present is equal to or less than the stated value.

From Poincelet, R.P. 1977. The biochemistry of composting, p.39. in: *Composting of Municipal Sludges and Wastes.* Proceedings of the National Conference, Rockville, MD. With permission.

the mesophilic bacteria and instead begin to favor the thermophilic bacteria. The resulting increased microbial activity of the thermophiles causes the temperature in the compost pile to rise to 65 to 70°C. Eventually, with the depletion of the food sources, overall microbial activity decreases and the temperature falls resulting in a second mesophilic phase during the cooling stage. As the readily available microbial food supply is consumed, the temperature falls to ambient and the material enters the maturation stage. Microbial activity is low during this stage, which can last a few months. Methods of determining compost maturity for horticultural applications are discussed in other chapters in this book.

B. Microbial Population

Composting is a complex process involving a wide array of microorganisms attacking organic wastes. The microorganisms that are mainly responsible for the composting process are fungi, actinomycetes, and bacteria, possibly also protozoas and algae.

The microbial population of bacteria, fungi, and actinomycetes changes during composting. The changes obtained during the windrow composting of biosolids and bark are shown in Figure 2.4 (Epstein, 1997; Walke, 1975).

According to Finstein and Morris (1974) bacteria thrive during all the stages of composting. Poincelet (1977) (Table 2.1), who analyzed the microbial population as a function of temperature, found that bacteria are usually present in large numbers throughout the whole composting period and are the major microbial species responsible for the degradation processes.
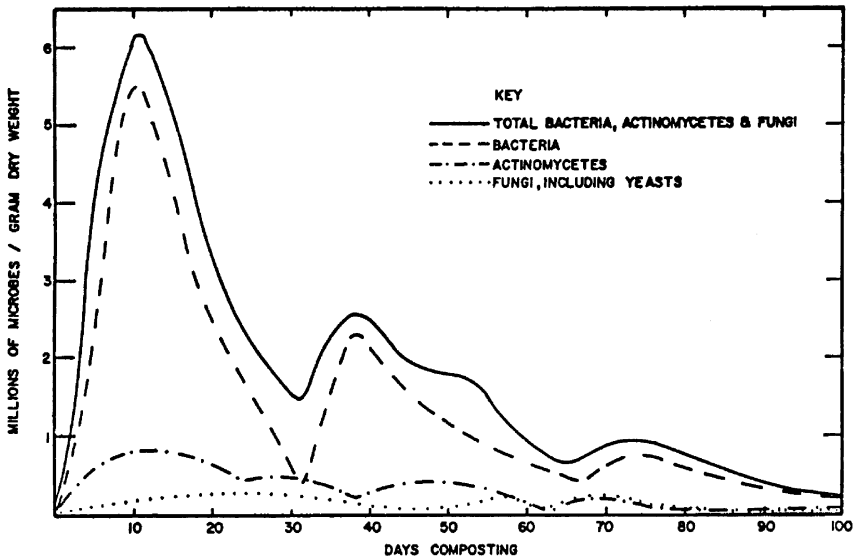
Figure 2.4   Fluctuation of microbial population within windrow during composting. (From Walke, R. 1975. The preparation, characterization and agricultural use of bark-sewage compost, p.47. PhD Thesis, The University of New Hampshire, Durham, New Hampshire).

1. *Bacteria*

In most cases, bacteria are about 100 times more prevalent than fungi (Table 2.1; Poincelet, 1977). Golueke (1977) estimated that at least 80 to 90% of the microbial activity in composting is due to bacteria (see Figure 2.4). Actual bacteria populations are dependent upon the feedstock, local conditions, and amendments used. Burford (1994) observed that at the start of the composting process a large number of species are present including *Streptococcus* sp., *Vibrio* sp., and *Bacillus* sp. with at least 2000 strains. Corominas et al. (1987), in his study of microorganisms in the composting of agricultural wastes, identified species belonging to the genera *Bacillus, Pseudomonas, Arthrobacter*, and *Alcaligenes,* all in the mesophilic stage. In the thermophilic stage, Strom (1985b) identified 87% of the thermophilic bacteria to be of the *Bacillus* sp. such as *B. subtilis, B. stearothermophilus*, and *B. licheniformis*. However, colony variety has been found to decrease as the temperature increases (Carlyle and Norman, 1941; Finstein and Morris, 1974). This observation is consistent with that noted by Webley (1947) who reported the variation in the numbers of aerobic mesophilic bacteria in a study of three separate composts. During the high-temperature stage of composting the mesophilic bacteria are at their lowest level while the thermophilic bacteria are prevalent. However, as temperatures decrease to below 40°C there is a striking repopulation by the mesophilic bacteria, which have been inactive during the thermophilic stage (Webley, 1947).

2. Actinomycetes

Actinomycetes belong to the order Actinomycetales. Although they are similar to fungi, in that they form branched mycelium (colonies), they are more closely related to bacteria. Usually they are not present in appreciable numbers until the composting process is well established. Visual growth of actinomycetes may be observed under favorable conditions, usually between 5 to 7 days into the composting process (Finstein and Morris, 1974; Golueke, 1977). When present in a composting process they can be readily detected due to their greyish appearance spreading throughout the composting pile. With in-vessel composting this greyish appearance of the actinomycetes may not be as prevalent because of the constant turning. Golueke (1977) also suggests that actinomycetes are responsible for the faint "earthy" smell that the compost emits under favorable conditions and which generally increases as the process proceeds. Species of the actinomycetes genera *Micromonospora*, *Streptomyces*, and *Actinomyces* can regularly be found in composting material. These species can be spore formers and are able to withstand adverse conditions, such as inadequate moisture. Because the actinomycetes can utilize a relatively wide array of compounds as substrates, they play an important role in the degradation of the cellulosic component. To some extent they can also decompose the lignin component of wood (Golueke, 1977).

3. Fungi

Fungi appear within the composting process about the same time as the actinomycetes. More types of fungi have been identified in the composting process than either the bacteria or the actinomycetes. Kane and Mullins (1973a) identified 304 unifungal isolates in one batch of compost in a solid waste reactor composting system in Florida. Two general growth forms in fungi exist — molds and yeasts. The most commonly observed species of cellulolytic fungi (Bhardwaj, 1995) in composting materials are *Aspergillus, Penicillin*, *Fusarium, Trichoderma,* and *Chaetomonium*. Although some fungi are very small, most are visible in the form of fruiting bodies — mushrooms — throughout the compost pile. While cellulose and hemicellulose (as in paper products) are slower to degrade than either sugars or starches, lignin is the most resistant organic waste and as such is usually the last in the food chain to be degraded (Epstein, 1997). However, the *Basidiomycetes*, or white rot fungi, play a very important role in the degradation of lignin.

The upper limit for fungal activity seems to be around 60°C. This inactivity of the mesophilic and thermophilic fungi above 60°C has been reported by Chang and Hudson (1967), Finstein and Morris (1974), Gray (1970), and Kane and Mullins (1973b). However, at temperatures below 60°C, the thermophilic fungi can recolonize the compost pile. At temperatures below 45°C, the mesophilic fungi reappear. One of the few thermophilic fungi that survive above 60°C is the thermotolerant species *Aspergillus fumigatus* (Haines, 1995). The spores of this species readily withstand temperatures above 60°C and this species becomes the dominant fungus in the compost pile at those temperatures. *Aspergilllus fumigatus* is a mold and has

a special significance as a cellulose and hemicellulose degrader (Fischer et al., 1998). However, the air borne spores can be a health hazard at the composting facility, to site workers who have a history of respiratory illnesses (Olver, 1994). Human health issues are discussed in more detail in other chapters in this book.

4. Pathogens

One of the requirements of a commercial operation is to maximize the destruction of pathogens that may be present in the composting feedstock. Theoretically, if the feedstock does not contain manures or biosolids there should be few enteric pathogens. However, where composting operations allow disposable diapers and pet feces to be a part of their waste collection, this may not be the case. Other nonenteric pathogens can be found in meat scraps (*Trichinella spiralis*) and viruses of human origin (poliovirus) have also been found in refuse (Golueke, 1977). As the temperature rises in the composting process the pathogens are usually destroyed as they reach their thermal death points (Table 2.2). Viruses are killed in about 25 min at 70°C (Roediger, 1964). There is a relationship between temperature and time for pathogen kill. A high temperature for a short period of time may be just as effective as a lower temperature for longer duration (Haug, 1993).

Table 2.2 Thermal Death Points for Some Common Pathogens and Parasites

Organism	50°C	55°C	60°C
Salmonella thyphosa	—	30 min	20 min
Salmonella sp.	—	60 min	15–20 min
Shigella sp.	—	60 min	—
Escherichia coli	—	60 min	15–20 min
Streptococcus pyogenes	—	10 min	
Mycobacterium diptheriae	—	45 min	—
Brucellus abortus or suis	—	60 min	3 min
Entamoeba histolytica (cysts)	—	1 sec	—
Trichinella spiralis	—	—	1 sec
Necator americanus	50 min	—	—
Ascaris lumbrigoides (ova)	—	60 min	—

Note: Data based on Burford (1994), Finstein and Morris (1974), Gotass (1956), Haug (1993), and Polprasert (1989).

The U.S. EPA in "Process to Further Reduce Pathogens" (Composting Council, 1993) established criteria for composts made with biosolids. According to the Federal Biosolids Technical Regulations, a windrow operation must reach a minimum temperature of 55°C for 15 days, with a minimum of five turnings. For an in-vessel or static pile system a minimum temperature of 55°C for 3 days is required. However, Hay (1996) suggested that bacterial regrowth may be possible under certain conditions following composting. Haug (1993) also indicated that a properly operated compost process should maintain an active population of nonpathogenic bacteria so as to prevent explosive regrowth of the pathogenic bacteria.

C. Recyclate

Several composting operators add amendments to their incoming feedstock to achieve desired properties. These amendments can include screened material, such as oversize wood chips, from previous runs. In studies conducted at our facilities (IPS at Joyceville, Ontario and Wright Environmental at Ste Anne des Plaines, Quebec), we found that the screened immature compost used as recyclate has attached microbial flora. This material, when mixed with the fresh feedstock, reintroduces microbial flora back into the composting process, facilitating the initiation of the compost process (Day et al., 1998).

III. CHEMICAL PROCESSES IN COMPOSTING

The fundamental elemental composition of compost is easy to determine using modern analytical equipment. Unfortunately the analytical precision usually far exceeds the sample homogeneity. Consequently, in the analysis of elemental composition, the question is not how accurate and reproducible are the analytical data, but how accurate and reproducible is the sample and how truly representative it is of the material being analyzed.

A. Elemental Composition: Carbon (C), Nitrogen (N), and the C:N Ratio

The elemental composition of the material processed at a composting operation is very much dependent upon the types of feed materials being processed. However, both C and N are essential to the composting process. Carbon provides the primary energy source, and N is critical for microbial population growth. For effective, efficient composting the correct C:N ratio is essential. Although various organic feedstocks have been successfully composted with C:N ratios varying from about 17 to 78 (McGaughey and Gotass, 1953; Nakasaki et al., 1992b), a much narrower range of between 25 to 35 is considered desirable (Hamoda et al., 1998; Keller, 1961; Schulze, 1962b). The concern at low C:N ratios is the loss of ammonia (NH_3) (Morisaki et al., 1989), but at higher levels slow rates of decomposition can be anticipated (Finstein and Morris, 1974).

Table 2.3 provides data for the C and N composition of a wide variety of possible compost feedstocks derived from a variety of reference sources. Clearly, organic feedstocks that can be processed by commercial composting operations can have a wide variety of C:N ratios. This requires that compost operators have a knowledge of their feedstocks to ensure that the desired mix for optimum composting is achieved. However, the C:N ratio is only one of a large number of variables that have to be controlled. Thus, computer programs have been developed to assist compost operators to achieve the desired mix for optimum composting (CRIQ, 1998; Naylor, 1996).

Although it is customary to express the C:N ratio as a function of the total concentration of C and N, this approach may not be appropriate for all materials (Kayhanian and Tchobanoglous, 1992) due to differences in the biodegradability

Table 2.3   Carbon and Nitrogen Composition of Some Compost Feedstocks (Based on Dry Wt. of Feedstocks)

Feedstock	C (%)	N (%)	C/N ratio	Reference
Urine	12.1	15.1	0.8	Polprasert, 1989
Fish scraps	32.8	8.2	4.0	Mathur, 1991
Activated sludge	35.3	5.6	6.3	Poincelet, 1977
Grass	41.6	2.46	17.0	Michel et al., 1993
Cow manure	30.6	1.7	18.0	Polprasert, 1989
Food waste	50	3.2	15.6	Kayhanian and Tchobanoglous, 1992
Yard waste	44.5	1.95	22.8	Kayhanian and Tchobanoglous, 1992
Leaves	44.5	0.93	48.0	Michel et al., 1993
Paper	43.3	0.25	173	Savage, 1996
Cardboard	48.2	0.20	254	Day et al., 1998
Sawdust	56.2	0.11	511	Willson, 1993

and bioavailability of different organic materials (Naylor, 1996). For example, Jeris and Regan (1973a) evaluated the compostability of a wide range of feedstocks and demonstrated the effect of different C sources. In the case of wood chips, which are frequently used as a bulking agent, not all woods have equal biodegradability (Allison, 1965); hardwoods are more biodegradable than softwoods. According to Chandler et al. (1980) these differences can, in part, be explained in terms of lignin content. More recently He et al. (1995) characterized the C content of compost into three classes — total extractable organic C, carbonate C, and residual C — and found the distribution on average to be 20%, 8%, and 72%, respectively.

Although the analysis for N content is usually more straightforward than for C, measurement of total Kjeldhal nitrogen (TKN) does not include all the nitrates and nitrites in the sample (Naylor, 1996). Fortunately, while TKN values range from 5000 to 60,000 mg·kg^{-1}, the concentrations of the nitrates and nitrites together are generally less than 100 mg·kg^{-1}.

Although the starting C:N ratio is important for effective and efficient composting, the final value is also important to determine the value of the finished compost as a soil amendment for growing crops. In general, a final C:N ratio of 15 to 20 is usually the range aimed for (Kayhanian and Tchobanoglous, 1993), although a value of 10 (Mathur, 1991) has been suggested as ideal. A final compost with a C:N ratio greater than 20 should be avoided since it could have a negative impact on plant growth and seed germination (Golueke, 1977). However, it is the availability of the C that is important, not the total measured C, so composts with C:N ratios higher than 20 can be acceptable when the C is not readily available (McGaughey and Gotass, 1953).

The composting process is essentially the bioconversion of biodegradable materials into carbon dioxide (CO_2) and H_2O. Consequently, it would be expected that the concentration of C in the compost material is reduced as composting proceeds, resulting in a corresponding reduction in the C:N ratio. In studies performed in our laboratory (Day et al., 1998), indeed, the concentration of C decreased during the composting process while that for N increased. As a result the C:N ratio decreased from 24.6 to 13.5 during 49 days of commercial composting. This was attributed to the loss in total dry mass due to losses of C as CO_2. These results are in keeping

with those reported by others for commercial composting processes (Grebus et al., 1994; Liao et al., 1995; Lynch and Cherry, 1996; Mato et al., 1994; McGaughey and Gotass, 1953; Sesay et al., 1998) or for laboratory simulated systems (Hamoda et al., 1998; Iannotti et al., 1993; Michel et al., 1993; Morisaki et al., 1989; Wiley et al., 1955; Witter and Lopez-Real, 1987). However, some studies have shown a decrease rather than an increase in the concentration of N (Liao et al., 1996; Poince-let, 1977; Snell, 1957). Despite the generally accepted decline in the C:N ratio with composting, ammonium-N (NH_4-N) and nitrate-N (NO_3-N) concentrations can also undergo changes. One study showed increases in these species (Grebus et al., 1994), but another study showed decreases (Canet and Pomares, 1995). Alternatively, several reports indicate increases in NH_3 levels during the initial stages of composting before the values level off and ultimately decline (Liao et al., 1995; Nakaski et al., 1992b; Palmisano et al., 1993; Shin and Jeong, 1996; Snell, 1957). By contrast, NO_3 concentrations typically show a decrease at the beginning of the composting process followed by a progressive increase towards the end (Neto et al., 1987). However, still other studies have shown that NO_3-N remains relatively constant (Palmisano et al., 1993). It is the possible formation of NH_3 that has to be controlled if odor complaints are to be avoided and N losses from the compost are to be minimized.

B. Other Elements

1. Phosphorus (P)

Other chemical elements present in compost feedstocks can influence the composting process, the quality of the compost produced, and the general acceptance of the composting process. Although compost feedstocks must have C and N to provide the fundamental nutrients to the living organisms for the composting process, phosphorus (P) is also an essential element especially in composting MSW (Brown et al., 1998). Although feedstocks such as biosolids, yard debris, and agriculture wastes may have sufficient P, MSW (because it is high in cellulose) may not have sufficient P for effective composting. The quantities of P along with N and potassium (K) present in the final material also are important in determining the quality of the compost product because they are essential nutrients for plant growth. Although not as critical as the C:N ratio, a C:P ratio of 100 to 200 seems to be desirable (Howe and Coker, 1992; Mathur, 1991). Phosphorus composition and the C:P ratio can vary widely depending upon the source of the feedstocks (Table 2.4).

Based upon the assumption that loss of C occurs during composting while P is not lost by volatilization or lixiviation, the percentage P in the compost would be expected to increase as composting proceeds. These effects have indeed been noted (Chandler et al., 1980; Cooperband and Middleton, 1996; Grebus et al., 1994; Mato et al., 1994) resulting in compost containing 0.2 to 0.7% P (Canet and Pomares, 1995; Fricke and Vogtmann, 1994; He et al., 1995; Warman and Termeer, 1996).

Table 2.4   Carbon and Phosphorus Composition of Various Feedstocks

Feedstock	C (%)	P (%)	C/P Ratio	Reference
Grass	41.6	0.26	160	Michel et al., 1993
Leaves	44.5	0.05	890	Michel et al., 1993
Leaves	49.9	0.2	250	Polprasert, 1989
Mixed paper	48.9	0.05	978	Kayhanian and Tchobanoglous, 1993
Yard waste	43.1	0.07	700	Kayhanian and Tchobanoglous, 1993
Food waste	44.6	0.08	557	Kayhanian and Tchobanoglous, 1993
Liquid sludge	41.4	0.17	244	Neto et al., 1987
Poultry manure/peat	42.7	0.90	47	Fernandes and Sartaj, 1997

2. Sulfur (S)

Sulfur concentrations are not usually measured in most scientific investigations of the composting process, but the presence of S in sufficient quantities can lead to the production of volatile, odorous compounds detectable at low level concentrations (Day et al., 1998; Toffey and Hentz, 1995). The major sources of S in compost materials are the two amino acids cysteine and methionine found in protein materials. Typical S levels for some composts and compost feedstocks are listed in Table 2.5. Under microbiological processing conditions (Stevenson, 1986) such as composting, both reduction and oxidative processes can occur. Under well-aerated conditions the sulfides are oxidized to the sulfates. However, under anaerobic conditions volatile organic sulfides and H_2S, which would otherwise be absorbed by the humic material and be oxidized, are just vaporized into the atmosphere. It is these compounds (specifically carbon disulfide, carbonyl sulfide, methyl mercaptan, diethyl sulfide, dimethyl sulfide, dimethyl disulfide, and hydrogen sulfide) that are responsible for many of the malodors associated with composting (Kissel et al., 1992; Kuroda et al., 1996; Miller et al., 1991; Toffey and Hentz, 1995). Both volatile S compounds and water soluble sulfate anions have been measured during MSW composting. Values ranged from a low of 0.05% to a high of 0.33% while a typical value appears to be about 0.16% (He et al., 1995).

Table 2.5   Sulfur Content of Various Feedstocks and Compost Samples

Material	S (%)	Reference
Mixed paper	0.079	Kayhanian and Tchobanoglous, 1993
Mixed paper	0.008	Kayhanian and Tchobanoglous, 1992
Yard waste	0.202	Kayhanian and Tchobanoglous, 1993
Yard waste	0.33	Kayhanian and Tchobanoglous, 1992
Food waste	0.219	Kayhanian and Tchobanoglous, 1993
Food waste	0.54	Duggan, 1991
Compost	0.25	Kayhanian and Tchobanoglous, 1993
Compost	0.37	Polprasert, 1989

3. Chlorine (Cl)

While S is an element of interest from an odor point of view, chlorine (Cl) attracts interest regarding concerns about chlorinated pesticides and polychlorinated biphenyls (PCB), as well as the polychlorinated dibenzodioxins (PCDD) and dibenzofurans (PCDF). Here the concern is the possible release of these materials from the compost to the soil and their subsequent uptake by plants, or possible leachate runoff. However, information on the fate of these and other chlorinated species during composting is limited (Brown et al., 1997; Fricke and Vogtmann, 1994; Hsu et al., 1993; Kim et al., 1995). Generally, the chlorinated pesticides typically found in MSW and destined for composting pose no environmental or health risks. In fact several of these compounds have been shown to be mineralized during the composting process (Brown et al., 1997; Hsu et al., 1993; Michel et al., 1996), suggesting that composting is a possible decontamination route. Although measurements of PCB levels in several organic waste streams in Germany (Fricke and Vogtmann, 1994) indicate no immediate concern, recommendations have been made for the introduction of efficient and effective ways to reduce possible source contamination, such as avoiding the use of pentachlorophenol-treated woods. Fricke and Vogtmann (1994) also reported that the levels of PCDDs and PCDFs found in composted materials were consistent with the ubiquitous levels found in the environment as a whole.

4. Heavy Metals

Heavy metals in compost are a concern to all commercial composting operators and play an important role in determining compost quality. In fact many countries have established, or are establishing, compost quality standards that limit the permissable concentrations for the metals arsenic, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, and zinc (Amlinger, 1996; Bourque et al., 1994; Chabbey, 1993; Chwastowska and Skalmowski, 1997; Composting Council, 1993; Genevini et al., 1997; Gies, 1997; Walker, 1996; Zucconi and de Bertoldi, 1987). Because of these regulations, many MSW composting facilities had to develop acceptable new procedures to restrict the introduction of possible contaminants in the feedstocks, by placing restrictions on specific materials (Richard and Woodbury, 1994). Table 2.6 provides a listing of the range of acceptable heavy metal levels for a variety of European countries (Gies, 1997) along with some typical values reported in the literature (Genevini et al., 1997; Vogtmann et al., 1993). Actual values depend very much on the raw materials being processed (Chabbey, 1993; Genevini et al., 1997; Kayhanian and Tchobanoglous, 1993; Mathur, 1991; Reinhart et al., 1993; Warman and Termeer, 1996). Because mineralization results in a reduction in organic content, the actual amounts of these heavy metals in the finished compost usually increase during composting (Chabbey, 1993). This means that although the original feedstock may have acceptable heavy metal levels, the concentration in the final compost may exceed regulatory levels. However, studies have shown that it is the chemical form of a heavy metal, rather than its presence, that is important in

Table 2.6 Heavy Metal Limits in European Compost Regulations and Measured Values (mg·kg^{−1})

Heavy Metals	Regulation Values[z]	MSW Compost[y]	Source Separation MSW Compost[y]	Biological Waste Compost[x]
Cd	1.2–4.0	4.4	1.22	0.84
Cr	50–750	90.8	34.9	35.8
Cu	60–1200	298.1	72.4	46.8
Pb	120–1200	455.0	147.4	83.1
Hg	0.3–25	—	—	0.38
Ni	20–400	76.3	17.5	20.5
Zn	200–4000	919.8	326.6	249.6

[z] After Gies, 1997.
[y] After Genevini et al., 1997.
[x] After Vogtmann et al., 1993.

determining compost quality, because the chemical form determines the metal's availability for plant uptake or leachability into the groundwater (Bourque et al., 1994; Chwastowska and Skalmowski, 1997; McBride, 1989; Petruzzelli et al., 1989; Tisdell and Breslin, 1995). These investigations suggest that although some MSW composts may contain heavy metals that exceed regulatory limits, only a small percentage of these metals may actually be bioavailable and pose health risks.

C. Chemical Functionality

Limited scientific information is available concerning the chemical reactions that occur during the composting processes. During composting approximately 50% of the organic matter is fully mineralized, producing CO_2 and H_2O. This applies specifically to the easily degradable materials such as protein, cellulose, and hemicellulose. Some of the organic material produces organic residuals, referred to as humic matter. This material has not received a great deal of attention until recently. Most of the early research in this area focused on extraction procedures to characterize the humic-like substances (Aoyama, 1991; Ciavatta et al., 1993; Jimenez and Garcia, 1992). However, more recently several research studies have been undertaken using sophisticated analytical techniques such as ^{13}C-NMR (carbon-13 nuclear magnetic resonance spectroscopy) (Chefetz et al., 1998b; Inbar et al., 1989; Preston et al., 1998), FTIR (Fourier-transform infrared spectroscopy) (Chefetz et al., 1998a; Inbar et al., 1989; Niemeyer et al., 1992; Proyenzano et al., 1998), pyrolysis-field ionization mass spectrometry (Schnitzer et al., 1993; van Bochove et al., 1996), and fluorescence spectroscopy (Chen et al., 1989; Senesi et al., 1991). These studies have provided some valuable information on the nature of the humic materials produced from a variety of waste streams, as well as the material sampled at various stages of maturity. The amount of humic acid (expressed as a percent of the organic matter) increases during composting (Chefetz et al., 1996; Inbar et al., 1990; Jimenez and Garcia, 1992; Roletto et al., 1985; Saviozzi et al., 1988). In terms of composition, research suggests that the following changes are taking place during composting:

- Aromatic structures increase (Chefetz et al., 1996; Chefetz et al., 1998b; Preston et al., 1998; Schnitzer et al., 1993)
- Phenolic structures increase (Chefetz et al., 1996; Chefetz et al., 1998b; Preston et al., 1998; Schnitzer et al., 1993)
- The proportion of carboxylic structures increase (Chefetz et al., 1996; Chefetz et al., 1998b; Preston et al., 1998; van Bochove et al., 1996)
- Alkyl structures remain essentially unchanged (Chefetz et al., 1998b; Schnitzer et al., 1993) or decrease slightly (Chefetz et al., 1996)
- O-alkyl structures decrease (Chefetz et al., 1998b; Preston et al., 1998)
- The concentration of amino acids appears to decrease (Chefetz et al., 1996; Proyenzano et al., 1998)
- The content of polysaccharides also decreases (Proyenzano et al., 1998)
- Data with respect to carbohydrates appear to be less consistent with studies showing no change (Schnitzer et al., 1993), increases (van Bochove et al., 1996), and decreases (Proyenzano et al., 1998)

D. Hydrogen Ion Concentration (pH)

The measurement of the pH of a compost sample is not a simple and straightforward procedure as most operators perceive. The actual pH measured is quite sensitive to sample size and sample preparation. Considerable variations in pH readings can be obtained from comparable samples unless standardized sampling and dilution procedures are used (Carnes and Lossin, 1971). Although the composting process is relatively insensitive to pH, because of the wide range of organisms involved (Epstein et al., 1977), the optimum pH range appears to be 6.5 to 8.5 (Jeris and Regan, 1973c; Willson, 1993). However, because of the natural buffering capacity of compost material, a much wider range of initial pH values can be tolerated (Willson, 1993). This allows a wide range of organic feedstocks to be composted whose pH can vary from a low of 5.0 to 6.5 for raw sludges (Haug, 1993) to highs of 11.0 for digested sludges treated with lime and ferric chloride (Shell and Boyd, 1969).

The initial pH of a typical MSW-based compost feedstock is usually slightly acidic (pH 6). During the early stages of composting the pH usually falls, due to the production of organic acids. However, as composting proceeds the pH becomes neutral again as these acids are converted to methane and CO_2. The pH of the final material is usually slightly alkaline (pH 7.5 to 8.5) (Poincelet, 1977; Polprasert, 1989; Snell, 1957). Compost mixtures with high pHs should be avoided because this can lead to loss of N as NH_3, and its associated odor problems (Miller et al., 1991). Slight increases in pH with composting time, following an initial drop in the early mesophilic stage, are characteristics of many composting studies involving agricultural wastes (Corominas et al., 1987), source-separated food wastes (Day et al., 1998; Shin and Jeong, 1996), and MSW (Burford, 1994; Canet and Pomares, 1995; Nakasaki et al., 1992b; Wiley et al., 1955). However, other reports do not show this initial drop in pH, but only a gradual increase in pH with time. Studies that show this type of behavior include those on MSW (Canet and Pomares, 1995; Jeris and Regan, 1973; Palmisano et al., 1993; Sesay et al., 1998), food wastes (Liao et al., 1995; Strom, 1985b), biosolids (McKinley and Vestal, 1985; Neto et al., 1987),

and yard wastes (Michel et al., 1993). Notably, only two studies have shown a decrease in pH with composting time (Lau et al., 1992; Mathur et al., 1990).

E. Respiratory Rates (O_2 Uptake/CO_2 Formation)

Composting is essentially an oxidation process where O_2 is consumed and CO_2 is produced. Consequently monitoring these two gases during the composting process can provide a reliable indication of composting activity. It is highly recommended that composting operators use O_2 and CO_2 meters to ensure that they have sufficient aeration (van der Werf and Ormseth, 1997) to supply the necessary O_2 and remove the CO_2. Studies generally show a 1:1 ratio between O_2 consumption and CO_2 generation (Harper et al., 1992; MacGregor et al., 1981; Wiley et al., 1955), but because CO_2 can be produced by anaerobic respiration and fermentation in addition to aerobic composting (Citterio et al., 1987) its measurement alone is not a good indication of compost activity. On the other hand, the measurement of O_2 consumption is a more suitable parameter for monitoring the compost process (Haug, 1993). In fact several studies have been conducted where O_2 levels have been used to control the composting process (Citterio et al., 1987; de Bertoldi et al., 1988). Although O_2 and CO_2 levels are usually measured in the gases exiting the compost pile, the in situ O_2 consumption and CO_2 accumulation are more important indicators of whether aerobic or anaerobic conditions prevail (Jackson and Line, 1998). Thus the adherence to recommended minimum O_2 levels of 5% (Schulze, 1962a) or 10% (Suler and Finstein, 1977) can be misleading, especially where O_2 diffusion rates are restricted.

Numerous studies have reported values of O_2 depletion and CO_2 evolution and related them to the composting process. Although most of the data have been obtained using laboratory scale reactors, several studies have been made using actual commercial compost piles. Because O_2 is required for composting, it is essential to ensure that adequate aeration is available. Several studies have actually calculated aeration requirements based on temperature (Wiley et al., 1955) and free air space (Snell, 1957). Regan and Jeris (1970) and Jeris and Regan (1973b) demonstrated the correlation between O_2 uptake and free air space, and also showed that O_2 uptake was highest at low moisture levels where more free air space was available.

Typically, during a composting run, the O_2 concentration in the exit gas from a compost reactor mirrors the changes in the CO_2 evolution and temperature curves (Day et al., 1998; Palmisano et al., 1993). The O_2 will decrease from its initial value of 21% to a value approaching 10% over the first few days of composting as the compost temperature increases and the CO_2 evolution increases. Subsequently, as the rate of composting decreases, the O_2 level should gradually increase, slowly returning to the 21% level as the temperatures start to approach ambient. Based upon several controlled tests it would appear that typical O_2 utilization rates for composting at 50 to 70°C are within the range of 1 to 10 mg $O_2 \cdot g^{-1} \cdot h^{-1}$ (Strom, 1985b).

Several researchers observed correlations between CO_2 production and O_2 uptake and also noted two regions of peak composting activity (Ashbolt and Line, 1982; Atkinson et al., 1996; Sikora et al., 1983; Sikora and Sowers, 1985; Wiley et al.,

1955). One peak is associated with the mesophilic phase and the other is associated with the thermophilic phase. Using CO_2 formation as a measure of composting activity, temperatures of 56 to 60°C were shown to be optimum for maximum compost activity (Jeris and Regan, 1973a; Kuter et al., 1985; Walke, 1975; Wiley et al., 1955). Higher temperatures can result in decreased activity (Schulze, 1962a), provided that O_2 levels are maintained between 10 and 18%. Measured rates for CO_2 evolution of about 5.9 mg·g^{-1}·h^{-1} (Kuter et al., 1985) are also of the order of these measured from O_2 consumption. More recently, Tseng et al. (1995) developed a kinetic model to determine the O_2 consumption and CO_2 evolution under controlled temperature and moisture conditions, which provides an insight into factors responsible for variations in microbial respiration and biomass formation.

The link between CO_2 evolution and O_2 consumption is sometimes referred to as the "respiratory quotient" (RQ). Typical RQ values for the composting process are usually about 0.9 (Atkinson et al., 1996; Schulze, 1960; Singley et al., 1982; Wiley et al., 1955). CO_2 evolution rates have been used by Nakasaki et al. (1985) to distinguish between thermophilic bacteria and thermophilic actimoycetes at different stages of composting. Nakasaki and his colleagues have used CO_2 evolution rates to study the different effects of a wide variety of factors such as moisture (Nakasaki et al., 1994), C:N ratio (Nakasaki et al., 1992b), feedstocks supplementations (Nakasaki et al., 1998), and O_2 concentration (Nakasaki et al., 1992a) on the composting process.

Several field measurements of O_2 and CO_2 have also been reported using both forced aeration and windrow turning. During these studies O_2 measurements were taken at various locations within the piles. In aerated piles, O_2 concentrations were highest in the lower pile sections and decreased on moving upwards (Epstein et al., 1976; Fernandes and Sartaj, 1997; Lynch and Cherry, 1996). In turned piles without aeration, the interior became rapidly depleted of O_2 soon after turning (Lynch and Cherry, 1996; Wiley and Spillane, 1962). O_2 concentration decreased sharply from 21 to about 10% as distance from the surface increased (Mato et al., 1994; Miller et al., 1991). This decrease in O_2 was accompanied by a corresponding increase in CO_2, which reached values as high as 60% in the interior (Miller et al., 1991). Clearly there is a need in aerated systems for a feedback loop to ensure O_2 levels do not fall too far, and to ensure that the CO_2 produced is swept out of the system (de Bertoldi et al., 1988; Hogan et al., 1989; MacGregor et al., 1981). Although temperature feedback loops are frequently employed (Finstein and Morris, 1974; Finstein et al., 1986; Hogan et al., 1989; MacGregor et al., 1981), O_2 feedback systems that maintain a 15 to 20% O_2 level within the compost pile (de Bertoldi et al., 1988) have advantages.

IV. PHYSICAL PROCESSES IN COMPOSTING

Although the composting process is a biochemical process, it is greatly influenced by physical factors such as moisture content and particle size. Both of these parameters can change during the composting process and influence the quality of compost and the time required to achieve a mature saleable product.

A. Moisture Content

The moisture content of compost is a critical criterion for optimum composting (Wiley, 1957). Optimum moisture values for a wide range of organic wastes were summarized by Jeris and Regan (1973b) with values ranging from 25 to 80%. However, it appears that moisture contents between 50 and 60% are most desirable (Bhardwaj, 1995; Golueke, 1989; Hachicha et al., 1992; Hamoda et al., 1998; McGaughey and Gotass, 1953; Miller, 1989; Neto et al., 1987; Poincelet, 1977; Stentiford, 1996). Water is essential for bacterial activity in the composting process (the nutrients for the microorganisms must be dissolved in water before they can be assimilated) (Fricke and Vogtmann, 1993; Hamoda et al., 1998). A minimum moisture content of 12 to 15% is essential for bacterial activity (Miller, 1989). However, even at levels of 45% or below, the moisture level can be rate limiting (Golueke, 1989; Jeris and Regan, 1973a; McGaughey and Gotass, 1953; Poincelet, 1977; Richard, 1992; Stentiford, 1996) causing composting facility operators to prematurely assume that their compost process has stabilized (Richard, 1992; Stentiford, 1996). On the other hand, excessive moisture in compost will prevent O_2 diffusion to the organisms, resulting in the material going anaerobic with the potential for odor formation (Golueke, 1989; Hamoda et al., 1998; McGaughey and Gotass, 1953; Poincelet, 1977; Wiley, 1957). A compost with too high a moisture content can also result in loss of nutrients and pathogens to the leachate, in addition to causing blockage of air passageways in the pile (Polprasert, 1989). Although moisture levels between 50 and 60% are generally accepted as optimum, detailed experiments performed by Snell (1957) suggested that for domestic garbage the range for optimum composting could be narrowed to between 52 to 58%. Suler and Finstein (1977) observed 60% to be the ideal moisture value for composting of food waste. Moisture in compost comes from two sources: moisture in the initial feedstock, and metabolic water produced by microbial action. Theoretical calculations by Finstein et al. (1983), Haug (1993), and Naylor (1996) suggest that between 0.6 and 0.8 g of water can be produced per gram of decomposed organic matter during composting. Experimental results suggest that the value is closer to 0.55 to 0.65 g per gram of organic material (Griffin, 1977; Wiley et al., 1955). However, the aerobic decomposition of 1 g of organic matter releases approximately 25 kJ of heat energy, which is enough to vaporize 10.2 g water (Finstein et al., 1986). Thus there is a tenfold excess of energy for water vaporization, which when coupled with losses due to aeration (Naylor, 1996) accounts for the major loss of water during composting. Typically, a compost operator would aim for an initial moisture content of about 60%, which during composting will decrease to about 40% to facilitate downstream processing such as sieving, mixing, and bagging (Fricke and Vogtmann, 1993).

The changes in moisture during composting are very dependent upon the feedstock bulking agents and method of composting. When outdoor windrow composting is being considered, environmental effects such as precipitation (Canet and Pomares, 1995; Lynch and Cherry, 1996) or the lack thereof (Reinhart et al., 1993) need to be considered. However, when external climatic conditions are eliminated, moisture levels decrease due to evaporation, as already noted (Day et al., 1998; Kuter et al., 1985; Liao et al., 1995; Liao et al., 1996; Neto et al., 1987; Papadimitriou and Balis,

1996; Sesay et al., 1998; Tseng et al., 1995; van der Werf and Ormseth, 1997). Consequently, in most commercial composting operations water addition may be required to maintain the desired biological activity (Kuter et al., 1985; Liao et al., 1995; Neto et al., 1987; Sesay et al., 1998; Tseng et al., 1995).

B. Particle Size

Another physical property of importance to the compost process is particle size. This not only affects moisture retention (Jeris and Regan, 1973b) but the free air space (Jeris and Regan, 1973b; Schulze, 1961) and porosity of the compost mixture (Naylor, 1996). Large particle size materials result in increased free air space and high porosity, but smaller particles result in the reverse effect. However, because aerobic decomposition occurs on the surface of particles, increasing the surface to volume ratio of the particles by decreasing particle size increases composting activity (Gotass, 1956; U.S. EPA, 1971; Willson, 1993). Consequently a compromise in particle size is required, with good results reported with material ranging in size from 3 to 50 mm in diameter (Gray and Biddlestone, 1974; Hamoda et al., 1998; Haug, 1993; Snell, 1991; Willson, 1993). The ideal free air space for optimum composting has been estimated to be 32 to 36% (Epstein, 1997). Jeris and Regan (1973b) calculated this range from field studies using a variety of materials with different densities and particle sizes, where the relationship between free air space, moisture, and O_2 consumption was determined. Fermor (1993) determined a similar value of 30%.

Compaction can also influence the free air space, although free air space is related to particle size. Any form of compaction that will reduce the free air space will reduce air permeably and increase resistance to air flow (Singley et al., 1982). In view of the importance of particle size distribution, compost operators usually employ grinding and sieving equipment to achieve material of the desired size for easier handling and processing (McGaughey and Gotass, 1953; Poincelet, 1977; Richard, 1992; Savage, 1996) when dealing with oversize wastes. However, when dealing with sludges and animal manures that contain fine particulate matter, organic amendments and/or bulking agents such as wood chips, sawdust, rice (*Oryza sativa* L.), straw, peat, rice hulls, etc. may be required to increase the free air space of the feedstock materials (Polprasert, 1989).

Although several methods exist for increasing the particle size distribution and air voids in compost (Day and Funk, 1994; Gabriels and Verdonck, 1992; Kayhanian and Tchobanoglous, 1993), Jeris and Regan (1973b) proposed that free air space be calculated from the bulk density (BD) and specific gravity (SG) of the material using the equation:

$$\text{Free Air Space} = 100\ (1 - BD/SG) \times \text{dry mass}$$

Although methods to measure air volume are available (Toffey and Hentz, 1995), most studies just report the bulk density as this is the easiest to measure, and from the operator's point of view, the most meaningful (van der Werf and Ormseth, 1997). Using data for samples taken from different depths in a compost pile (Brouillette et

al., 1996), it is possible to plot both the measured porosity and free air space as a function of bulk density. From these data (shown in Figure 2.5), it is possible to establish the following relationships among bulk density (BD), porosity (P), and free air space (FAS):

$$P = 100.3 — 0.0263\ BD$$

$$FAS = 99.5 — 0.0788\ BD$$

The bulk densities for a variety of compost feedstocks, which are presented in Table 2.7, merely represent typical values reported in the literature, and in many cases the moisture content and particle size distribution have not been provided. Similarly, bulk density values of initial and final composts reported in the literature show wide variations from a low of 178 $kg·m^{-3}$ to a high of 740 $kg·m^{-3}$ (Grebus et al., 1994; He et al., 1995; Howe and Coker, 1992; Kayhanian and Tchobanoglous, 1993; Marugg et al., 1993; Reinhart et al., 1993). During composting, the bulk density of compost would be expected to increase due to the breakdown in the particle size of the material. This results in a more compact compost, as confirmed by several studies (Jackson and Line, 1998; Kayhanian and Tchobanoglous 1993; Marugg et al., 1993; Reinhart et al., 1993; van der Werf and Ormseth, 1997). However, in some compost systems where substantial evaporation and loss of water is possible, the measured bulk density may decrease as the material dries out during the composting period (Day et al., 1998).
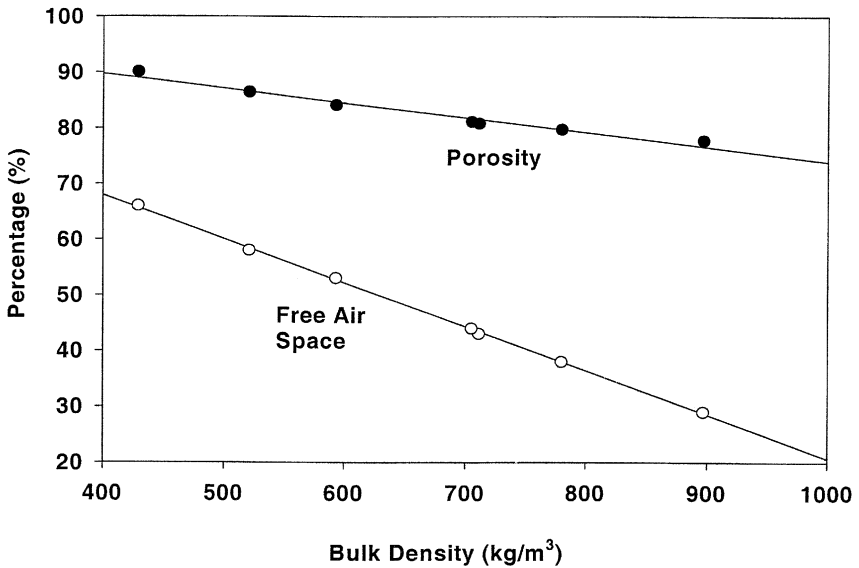
Figure 2.5 Relationship between porosity, free air space, and bulk density. (Using data from Brouillette, M., L. Trepanier, J. Gallichand, and C. Beauchamp.1996. Composting paper mill deinking sludge with forced aeration. *Canadian Agricultural Engineering* 38(2):115–122.)

Table 2.7   Typical Bulk Densities for Some Compost Feedstocks

Feedstock	Bulk Density (kg.m^{-3})	Reference
Mixed paper	80	Kayhanian and Tchobanoglous, 1993
Cardboard	130	Day et al., 1998
Yard waste	215	Reinhart et al., 1993
Yard waste	330	Day et al., 1998
Food waste	352	Kayhanian and Tchobanoglous, 1993
Leaves (shredded)	420	Howe and Coker, 1992
Restaurant waste	990	Day et al., 1998
Dewatered biosolids	1010	Glass, 1993

V. OVERALL CHANGES

A. Changes in Temperature

Temperature is a key factor affecting biological activity within a composting operation and is one factor that is maintained and controlled in any composting operation to ensure optimum growth and activity of the microbes. However, temperature is only a manifestation of the heat energy being released by the metabolic oxidation of the organic matter by microbes. A wide range of microorganisms exist in a composting environment and each has its own optimum temperature for growth. Mesophiles prefer temperatures around 15 to 45°C, while thermophiles prefer temperatures between 45 to 70°C (Burford, 1994; Finstein, 1992; Golueke, 1989; Poincelet, 1977). Although temperature is viewed by most compost operators as a key operating parameter and is used by many to control the process and optimize the degradation, it is only part of the whole thermodynamics of the process (Finstein et al., 1986; Harper et al., 1992; Haug, 1993; MacGregor et al., 1981; Naylor, 1996). However, when dealing with similar feedstocks of reproducible heat capacities, moisture contents, and porosities in piles of reproducible dimensions, temperature is an exceedingly useful tool for following and controlling the composting process. For the compost operator, the temperature of the compost is important for two reasons: (1) to maximize the decomposition rate and (2) to produce a "safe" product by maximizing pathogenic inactivation (Mathur, 1991; Polprasert, 1989; Stentiford, 1987).

Some debate exists concerning optimum temperature conditions for composting. These differences of opinion seem to originate because of the different feedstocks used in the different studies (Epstein, 1997). A temperature of about 55°C seems to be most commonly aimed for (Polparsert, 1989) with operating temperature ranges between 35 to 60°C considered normal. This temperature range also allows the operator to reconcile the trade-offs between pathogenic reduction and maximized biological activity.

Because of the simplicity of its measurement, most compost operators use temperature regulation as a means of controlling the compost operation. Operators typically link air ventilation with a temperature feedback control mechanism. In

standard windrow operations this can be accomplished by monitoring the temperature with a thermometer and turning the pile when required (Atkinson et al., 1996). In more sophisticated operations this can involve negative pressure aeration or forced air ventilation (Stentiford, 1987), and a wide variety of systems have been developed and evaluated in both bench scale (Hogan et al., 1989; Sikora et al., 1983; Suler and Finstein, 1977; Tseng et al., 1995) and commercial operations (Finstein et al., 1987; Lau et al., 1992; MacGregor et al., 1981; Sesay et al., 1998).

In nearly all scientific studies of the composting process, temperature–time relationships are usually presented to represent the rate of microbiological activity as a function of time. In most of these cases, the data show the typical temperature–time response, illustrated in Figures 2.2 and 2.3. Initially the temperature of the compost usually increases rapidly to about 40°C within the first 24 hours, as the population of mesophilic microbes is established. At this point the temperature may show an actual decrease for approximately 24 hours (see Figure 2.3) (Canet and Pomares, 1995; Day et al., 1998; Liao et al., 1996; Papadimitriou and Balis, 1996; Sikora et al., 1983). The temperature usually then increases rapidly into the thermophilic range, reaching peak temperatures of about 65°C over the next 2 or 3 days. These temperatures can usually be maintained for about 7 days before decreasing. However, because optimum decomposition has been shown to occur around 55°C (Bach et al., 1984; Epstein, 1997; Jeris and Regan, 1973a; McKinley et al., 1985; Suler and Finstein, 1977; Wiley, 1957), turning and/or aeration may be applied to achieve maximum degradation rates, which can be maintained for a longer period of time. Although studies with MSW compost have shown the temperature to drop 5 to 10°C as a result of the turning process, temperatures within the center of these piles were rapidly reestablished (Canet and Pomares, 1995; Fischer et al., 1998; Kochtitzky et al., 1969; Papadimitriou and Balis, 1996; Wiley and Spillane, 1962). During normal composting operations the temperature of the compost then gradually cools down as the mineralizable organic material is consumed, with the temperature gradually approaching ambient. However, within static piles and aerated bed systems, the temperature distribution can vary widely from the center of the piles to the outer layers. This effect has been noted in controlled laboratory experiments (Finstein et al., 1986; Liao et al., 1996) as well as in full-scale systems using both passive aeration (Fischer et al., 1998; Lynch and Cherry, 1996; Sartaj et al., 1995) and forced aeration (Epstein et al., 1976; Fernandes and Sartaj, 1997; Kuter et al., 1985; Sesay et al., 1998). In all test cases the hottest temperatures are recorded near the middle of the piles, while the coolest temperatures are recorded near the surfaces. Because of the need for a minimum temperature of about 20°C to maintain mesophilic activity, the question of the effect of harsh winters on year-round composting needs to be addressed for those operations in northern climates such as Canada (Lynch and Cherry, 1996). While in-vessel composting is one solution to this dilemma, passively aerated windrow systems also can be used at temperatures ranging from –27° to 15°C (Brouillette et al., 1996; Lynch and Cherry, 1996). Under these conditions the metabolic activity is principally mesophilic and the use of insulating materials, such as peat or finished compost, may be desirable for heat retention (Fernandes and Sartaj, 1997; Lynch and Cherry, 1996).

B. The Mineralization Process

One of the major objectives of any aerobic composting process is the transformation of a purifactable organic waste stream into a stabilized soil amendment that will improve soil physical properties, increase soil buffer capacity, add plant nutrients to the soil, increase soil water-holding capacity, and support and enhance a microbial population (Epstein, 1997).

In simplistic terms, compost can be considered to be composed of water, organic matter, and inorganic matter. The amount of water in a sample is usually determined by appropriate drying methods, whereas the organic and inorganic fractions are determined by a combustion process. The organic fraction is burned and volatilized leaving an ash residue considered to be the inorganic faction. The combustible fraction, sometimes referred to as the volatile solids, is a good indication of the organic content (Naylor, 1996). While most compost feedstocks have high volatile solids contents, these values can vary from a low of 65% noted for dewatered biosolids (Glass, 1993) to a high of about 99% for newspaper (Jeris and Regan, 1973a; Tchobanoglous et al., 1993). Typical values for a variety of compost feedstocks are provided in Table 2.8. Values for volatile solids reported for commercial compost operations vary from 23.2 to 85.7% depending upon the type of feedstocks being processed (He et al., 1995), although values between 55 to 80% are more common (Canet and Pomares, 1995; Day et al., 1998; Glass, 1993; Sikora and Sowers, 1985; Witter and Lopez-Real, 1987).

Table 2.8 Typical Volatile Solids for Some Compost Feedstocks (Dry Mass Basis)

Feedstock	Volatile Solids (%)	Reference
Dewatered biosolids	65	Glass, 1993
Poultry manure	77	Sartaj et al., 1995
Biosolids	85	Kosaric and Velayudhan, 1991
Food waste	84	Tchobanoglous et al., 1993
Food waste	86.3	Shin and Jeong, 1996
Food waste	96.8	Kayhanian and Tchobanoglous, 1992
Grass	89	Michel et al., 1993
Yard wastes	93.2	Tchobanoglous et al., 1993
Office paper	85.7	Shin and Jeong, 1996
Office paper	94.0	Tchobanoglous et al., 1993
Food wastes	96.8	Kayhanian and Tchobanoglous, 1992
Newspaper	95.6	Shin and Jeong, 1996
Newspaper	98.5	Tchobanoglous et al., 1993
Newspaper	99.5	Jeris and Regan, 1973a

During the composting process the ash or inorganic component increases due to the loss of the organic fraction or volatile solids as CO_2. Consequently, the measurement of ash content is a crude indicator of extent of composting. However, the measurement of ash content alone tends to lack sensitivity due to its dependence upon sampling practices (Papadimitriou and Balis, 1996) and sample sizes taken (Atkinson et al., 1996). Wiley et al. (1955) performed a mass balance of compost

and found that, in general, losses in volatile solids varied from 17 to 53% with an average of 30%. This suggests that approximately one third of the organic material is decomposed into water and CO_2. However, losses in volatile solids are very much dependent upon the feedstocks used. In the case of MSW composting studies, volatile solids loss values close to 30% have been recorded (Brown et al., 1998; Harper et al., 1992; Iannotti et al., 1993; Poincelet, 1977; Tseng et al., 1995), while other studies have shown losses of about 10 to 15% (Canet and Pomares, 1995; de Bertoldi et al., 1988; Kuter et al., 1985) or intermediate values close to 20% (Day et al., 1998; McGaughey and Gotass, 1953). As would be expected, the values can be influenced by aeration (Sesay et al., 1998) and temperature control (Tseng et al., 1995) as well as nutrient level (Brown et al., 1998). When grass or leaf mixtures were composted, the decreases in volatile solids were close to 30%, with the greatest losses being associated with mixtures containing the larger quantities of grass (Michel et al., 1993). For biosolids the losses in volatile solids are very much dependent upon the bulking agents used. With straw as a bulking agent, the losses in volatile solids were 24% (Witter and Lopez-Real, 1987). However, when fewer biodegradable bulking agents were employed the losses were less than 10% (Liao et al., 1996; McKinley and Vestal, 1985). Similar results have been noted for animal manure (Sartaj et al., 1995; Lynch and Cherry, 1996).

VI. SUMMARY

Many biological, chemical, and physical changes take place during the composting process. Under the influence of microbial attack, many of the organic compounds such as carbohydrates, sugars, and cellulose undergo chemical transformations producing heat, water, and CO_2 in addition to a wide variety of new and modified chemical species. The transformations not only provide valuable information on the actual composting process, but many can be used as control mechanisms to achieve optimum composting and a beneficial product. A knowledge of these fundamental changes is important if composting is to become a widely acceptable technology for the recovery of the organic fraction from our waste stream.

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