The Science and Engineering of Composting
Background Information

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Background Information

Invertebrates of the Compost Pile

In small-scale outdoor composting systems, such as backyard compost piles, soil invertebrates are likely to contribute to the decomposition process. Together with bacteria, fungi, and other microbes, these organisms make up a complex food web or energy pyramid with primary, secondary, and tertiary level consumers. The base of the pyramid, or energy source, is made up of organic matter including plant and animal residues.

**Tertiary Consumers** (organisms that eat secondary consumers) centipedes, predatory mites, rove beetles, fomicid ants, carabid beetles

**Secondary Consumers** (organisms that eat primary consumers) springtails, some types of mites, feather-winged beetles nematodes, protozoa, rotifera, soil flatworms

**Primary Consumers** (organisms that eat organic residues) bacteria, fungi, actinomycetes, nematodes, some types of mites, snails, slugs, earthworms, millipedes, sowbugs, whiteworms

**Organic Residues** leaves, grass clippings, other plant debris, food scraps, fecal matter and animal bodies including those of soil invertebrates

As you can see in this pyramid, organic residues such as leaves or other plant materials are eaten by some types of invertebrates such as millipedes, sow bugs, snails and slugs. These invertebrates shred the plant materials, creating more surface area for action by fungi, bacteria, and actinomycetes (a group of organisms intermediate between bacteria and true fungi), which are in turn eaten by organisms such as mites and springtails.

Many kinds of worms, including earthworms, nematodes, red worms and potworms eat decaying vegetation and microbes and excrete organic compounds that enrich compost. Their tunneling aerates the compost, and their feeding increases the surface area of organic matter for microbes to act upon. As each decomposer dies or excretes, more food is added to web for other decomposers.

**Nematodes**: These tiny, cylindrical, often transparent microscopic worms are the most abundant of the physical decomposers - a handful of decaying compost contains several million. It has been estimated that one rotting apple contains 90,000. Under a magnifying lens they resemble fine human hair. Some species scavenge on decaying vegetation, some feed on bacteria, fungi, protozoa and other nematodes, and some suck the juices of plant roots, especially root vegetables.

**Mites**: Mites are the second most common invertebrate found in compost. They have eight leg-like jointed appendages. Some can be seen with the naked eye and others are microscopic. Some can be seen hitching rides on the back of other faster moving invertebrates such as sowbugs, millipedes, and beetles. Some scavenge on leaves, rotten wood, and other organic debris. Some species eat...
fungi, yet others are predators and feed on nematodes, eggs, insect larvae and other mites and springtails. Some are both free living and parasitic. One very common compost mite is globular in appearance, with bristling hairs on its back and red orange in color.

**Springtails**: Springtails are extremely numerous in compost. They are very small wingless insects and can be distinguished by their ability to jump when disturbed. They run in and around the particles in the compost and have a small spring-like structure under the belly that catapults them into the air when the spring catch is triggered. They chew on decomposing plants, pollen, grains, and fungi. They also eat nematodes and droppings of other arthropods and then meticulously clean themselves after feeding.

**Earthworms**: Earthworms do the lion's share of the decomposition work among the larger compost organisms. They are constantly tunneling and feeding on dead plants and decaying insects during the daylight hours. Their tunneling aerates the compost and enables water, nutrients and oxygen to filter down. "As soil or organic matter is passed through an earthworm's digestive system, it is broken up and neutralized by secretions of calcium carbonate from calciferous glands near the worm's gizzard. Once in the gizzard, material is finely ground prior to digestion. Digestive intestinal juices rich in hormones, enzymes, and other fermenting substances continue the breakdown process. The matter passes out of the worm's body in the form of casts, which are the richest and finest quality of all humus material. Fresh casts are markedly higher in bacteria, organic material, and available nitrogen, calcium, magnesium, phosphorus and potassium than soil itself." (Rodale)

**Slugs and snails (left)**: Slugs and snails generally feed on living plant material but will attack fresh garbage and plant debris and will therefore appear in the compost heap.

**Centipedes**: Centipedes are fast moving predators found mostly in the top few inches of the compost heap. They have formidable claws behind their head which possess poison glands that paralyze small red worms, insect larvae, newly hatched earthworms, and arthropods - mainly insects and spiders.

**Millipedes**: They are slower and more cylindrical than centipedes and have two pairs of appendages on each body segment. They feed mainly on decaying plant tissue but will eat insect carcasses and excrement.
**Sow Bugs:** Sow Bugs are fat bodied crustaceans with delicate plate-like gills along the lower surface of their abdomens which must be kept moist. They move slowly grazing on decaying vegetation.

**Beetles:** The most common beetles in compost are the rove beetle, ground beetle and feather-winged beetle. Feather-winged beetles feed on fungal spores, while the larger rove and ground beetles prey on other insects, snails, slugs and other small animals.

**Ants:** Ants feed on aphid honeydew, fungi, seeds, sweets, scraps, other insects and sometimes other ants. Compost provides some of these foods and it also provides shelter for nests and hills. Ants may benefit the compost heap by moving minerals especially phosphorus and potassium around by bringing fungi and other organisms into their nests.

**Flies:** During the early stages of the composting process, flies provide ideal airborne transportation for bacteria on their way to the pile. Flies spend their larval phase in compost as maggots, which do not survive thermophilic temperatures. Adults feed upon organic vegetation.

**Spiders:** Spiders feed on insects and other small invertebrates.

**Pseudoscorpions:** Pseudoscorpions are predators which seize victims with their visible front claws, then inject poison from glands located at the tips of the claws. Prey include minute nematode worms, mites, larvae, and small earthworms.

**Earwigs:** Earwigs are large predators, easily seen with the naked eye. They move about quickly. Some are predators. Others feed chiefly on decayed vegetation.

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**Compost Microorganisms**

by Nancy Trautmann and Elaina Olynciw

**The Phases of Composting**

In the process of composting, microorganisms break down organic matter and produce carbon dioxide, water, heat, and humus, the relatively stable organic end-product. Under optimal conditions, composting proceeds through three phases: 1) the mesophilic, or moderate-temperature phase, which lasts for a couple of days, 2) the thermophilic, or high-temperature phase, which can last from a few days to several months, and finally, 3) a several-month cooling and maturation phase.
Different communities of microorganisms predominate during the various composting phases. Initial decomposition is carried out by mesophilic microorganisms, which rapidly break down the soluble, readily degradable compounds. The heat they produce causes the compost temperature to rapidly rise.

As the temperature rises above about 40°C, the mesophilic microorganisms become less competitive and are replaced by others that are thermophilic, or heat loving. At temperatures of 55°C and above, many microorganisms that are human or plant pathogens are destroyed. Because temperatures over about 65°C kill many forms of microbes and limit the rate of decomposition, compost managers use aeration and mixing to keep the temperature below this point.

During the thermophilic phase, high temperatures accelerate the breakdown of proteins, fats, and complex carbohydrates like cellulose and hemicellulose, the major structural molecules in plants. As the supply of these high-energy compounds becomes exhausted, the compost temperature gradually decreases, and mesophilic microorganisms once again take over for the final phase of "curing" or maturation of the remaining organic matter.

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Bacteria

Bacteria are the smallest living organisms and the most numerous in compost; they make up 80 to 90% of the billions of microorganisms typically found in a gram of compost. Bacteria are responsible for most of the decomposition and heat generation in compost. They are the most nutritionally diverse group of compost organisms, using a broad range of enzymes to chemically break down a variety of organic materials.

Bacteria are single-celled and structured as either rod-shaped bacilli, sphere-shaped cocci or spiral-shaped spirilla. Many are motile, meaning that they have the ability to move under their own power. At the beginning of the composting process (0-40°C), mesophilic bacteria predominate. Most of these are forms that can also be found in topsoil.

As the compost heats up above 40°C, thermophilic bacteria take over. The microbial populations during this phase are dominated by members of the genus Bacillus. The diversity of bacilli species is fairly high at temperatures from 50-55°C but decreases dramatically at 60°C or above. When conditions become unfavorable, bacilli survive by forming endospores, thick-walled spores that are highly resistant to heat, cold, dryness, or lack of food. They are ubiquitous in nature and become active whenever environmental conditions are favorable.

At the highest compost temperatures, bacteria of the genus Thermus have been isolated. Composters sometimes wonder how microorganisms evolved in nature that can withstand the high temperatures found in active compost. Thermus bacteria were first found in hot springs in Yellowstone National Park and may have evolved there. Other places where thermophilic conditions exist in nature include deep sea thermal vents, manure droppings, and accumulations of decomposing vegetation that have the right conditions to heat up just as they would in a compost pile.

Once the compost cools down, mesophilic bacteria again predominate. The numbers and types of mesophilic microbes that recolonize compost as it matures depend on what spores and organisms are present in the compost as well as in the immediate environment. In general, the longer the curing or maturation phase, the more diverse the microbial community it supports.

Actinomycetes

The characteristic earthy smell of soil is caused by actinomycetes, organisms that resemble fungi but are filamentous bacteria. Like other bacteria, they lack nuclei, but they grow multicellular filaments like fungi. In composting they play an important role in degrading complex organics such as cellulose, lignin, chitin, and proteins. Their enzymes enable them to chemically break down tough debris such as woody stems, bark, or newspaper.

Some species appear during the thermophilic phase, and others become important during the cooler curing phase, when only the most resistant compounds remain in the last stages of the formation of humus.
Actinomycetes form long, thread-like branched filaments that look like gray spider webs stretching through compost. These filaments are most seen toward the end of the composting process, in the outer 10 to 15 centimeters of the pile. Sometimes they appear as circular colonies that gradually expand in diameter.

**Fungi**
Fungi include molds and yeasts, and collectively they are responsible for the decomposition of many complex plant polymers in soil and compost. In compost, fungi are important because they break down tough debris, enabling bacteria to continue the decomposition process once most of the cellulose has been exhausted. They spread and grow vigorously by producing many cells and filaments, and they can attack organic residues that are too dry, acidic, or low in nitrogen for bacterial decomposition.

Most fungi are classified as saprophytes because they live on dead or dying material and obtain energy by breaking down organic matter in dead plants and animals. Fungal species are numerous during both mesophilic and thermophilic phases of composting. Most fungi live in the outer layer of compost when temperatures are high. Compost molds are strict aerobes that grow both as unseen filaments and as gray or white fuzzy colonies on the compost surface.

**Protozoa**
Protozoa are one-celled microscopic animals. They are found in water droplets in compost but play a relatively minor role in decomposition. Protozoa obtain their food from organic matter in the same way as bacteria do but also act as secondary consumers ingesting bacteria and fungi.

**Rotifers**
Rotifers are microscopic multicellular organisms also found in films of water in the compost. They feed on organic matter and ingest bacteria and fungi.

**Acknowledgments**
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Compost Chemistry

C/N Ratio

Of the many elements required for microbial decomposition, carbon and nitrogen are the most important. Carbon provides both an energy source and the basic building block making up about 50 percent of the mass of microbial cells. Nitrogen is a crucial component of the proteins, nucleic acids, amino acids, enzymes, and co-enzymes necessary for cell growth and function.

To provide optimal amounts of these two crucial elements, you can use the carbon-to-nitrogen (C/N) ratio for each of your compost ingredients. The ideal C/N ratio for composting is generally considered to be around 30:1, or 30 parts carbon for each part nitrogen by weight. Why 30:1? At lower ratios, nitrogen will be supplied in excess and will be lost as ammonia gas, causing undesirable odors. Higher ratios mean that there is not sufficient nitrogen for optimal growth of the microbial populations, so the compost will remain relatively cool, and degradation will proceed at a slow rate.

Typical C/N ratios for common compost materials can be looked up in published tables such as Appendix A of the On-Farm Composting Handbook. In general, materials that are green and moist tend to be high in nitrogen, and those that are brown and dry are high in carbon. High nitrogen materials include grass clippings, plant cuttings, and fruit and vegetable scraps. Brown or woody materials such as autumn leaves, wood chips, sawdust, and shredded paper are high in carbon. You can calculate the C/N ratio of your compost mixture, or you can estimate optimal conditions simply by using a combination of materials that are high in carbon and others that are high in nitrogen.

<table>
<thead>
<tr>
<th>Materials High in Carbon</th>
<th>C:N</th>
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<tbody>
<tr>
<td>Autumn Leaves</td>
<td>30-80:1</td>
</tr>
<tr>
<td>Straw</td>
<td>40-100:1</td>
</tr>
<tr>
<td>Wood chips or sawdust</td>
<td>100-500:1</td>
</tr>
<tr>
<td>Bark</td>
<td>100-130:1</td>
</tr>
<tr>
<td>Mixed paper</td>
<td>150-200:1</td>
</tr>
<tr>
<td>Newspaper or corrugated cardboard</td>
<td>560:1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials High in Nitrogen</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable scraps</td>
<td>15-20:1</td>
</tr>
<tr>
<td>Coffee grounds</td>
<td>20:1</td>
</tr>
<tr>
<td>Grass clippings</td>
<td>15-25:1</td>
</tr>
<tr>
<td>Manure</td>
<td>5-25:1</td>
</tr>
</tbody>
</table>


As composting proceeds, the C/N ratio gradually decreases from 30:1 to 10-15:1 for the finished product. This occurs because each time that organic compounds are consumed by microorganisms, two-thirds of the carbon is given off as carbon dioxide. The remaining third is incorporated along with nitrogen into microbial cells, then later released for further use once those cells die.

Although attaining a C/N ratio of roughly 30:1 is a useful goal in planning composting operations, this ratio may need to be adjusted according to the bioavailability of the materials in question. Most of the nitrogen in compostable materials is readily available. Some of the carbon, however, may be bound up in compounds that are highly resistant to biological degradation. Newspaper, for example, is slower than other types of paper to break down because it is made up of cellulose fibers sheathed in lignin, a highly resistant compound found in wood. Corn stalks and straw are similarly slow to break down because they are made up of a resistant form of cellulose. Although all of these materials can still be composted, their relatively slow rates of
decomposition mean that not all of their carbon will be readily available to microorganisms, so a higher initial C/N ratio can be planned. Particle size also is a relevant consideration; although the same amount of carbon is contained in comparable masses of wood chips and sawdust, the larger surface area in the sawdust makes its carbon more readily available for microbial use.

**Oxygen**

Another essential ingredient for successful composting is oxygen. As microorganisms oxidize carbon for energy, oxygen is used up and carbon dioxide is produced. Without sufficient oxygen, the process will become anaerobic and produce undesirable odors, including the rotten-egg smell of hydrogen sulfide gas.

So, how much oxygen is sufficient to maintain aerobic conditions? Although the atmosphere is 21% oxygen, aerobic microbes can survive at concentrations as low as 5%. Oxygen concentrations greater than 10% are considered optimal for maintaining aerobic composting. Some compost systems are able to maintain adequate oxygen passively, through natural diffusion and convection. Other systems require active aeration, provided by blowers or through turning or mixing the compost ingredients.

**Nutrient Balance**

Adequate phosphorus, potassium, and trace minerals (calcium, iron, boron, copper, etc.) are essential to microbial metabolism. Normally these nutrients are not limiting because they are present in ample concentration in the compost source materials.

**pH**

A pH between 5.5 and 8.5 is optimal for compost microorganisms. As bacteria and fungi digest organic matter, they release organic acids. In the early stages of composting, these acids often accumulate. The resulting drop in pH encourages the growth of fungi and the breakdown of lignin and cellulose. Usually, the organic acids become further broken down during the composting process. If the system becomes anaerobic, however, acid accumulation can lower the pH to 4.5, severely limiting microbial activity. In such cases, aeration usually is sufficient to return the compost pH to acceptable ranges.

**Compost Physics**

The rate at which composting occurs depends on physical as well as chemical factors. Temperature is a key parameter determining the success of composting operations. Physical characteristics of the compost ingredients, including moisture content and particle size, affect the rate at which composting occurs. Other physical considerations include the size and shape of the system, which affect the type and rate of aeration and the tendency of the compost to retain or dissipate the heat that is generated.

**Temperature Curve**

Compost heat is produced as a by-product of the microbial breakdown of organic material. The heat production depends on the size of the pile, its moisture content, aeration, and C/N ratio. Additionally, ambient (indoor or outdoor) temperature affects compost temperatures.

You can chart the health and progress of your compost system by taking periodic temperature measurements. A typical temperature curve for an unturned pile is shown below. How do you think that periodic turning would change this curve?
A well-designed indoor compost system, >10 gallons in volume, will heat up to 40-50°C in two to three days. Soda bottle bioreactors, because they are so small, are more likely to peak at temperatures of 30-40°C. At the other end of the range, commercial or municipal scale compost systems may take three to five days to heat up and reach temperatures of 60-70°C. Compost managers strive to keep the compost below about 65°C because hotter temperatures cause the beneficial microbes to die off. If the pile gets too hot, turning or aerating will help to dissipate the heat.

Decomposition occurs most rapidly during the *thermophilic* stage of composting (40-60°C), which lasts for several weeks or months depending on the size of the system and the composition of the ingredients. This stage also is important for destroying thermosensitive pathogens, fly larvae, and weed seeds. In outdoor systems, compost invertebrates survive the thermophilic stage by moving to the periphery of the pile or becoming dormant. Regulations by the U.S. Environmental Protection Agency specify that to achieve a significant reduction of pathogens during composting, the compost should be maintained at minimum operating conditions of 40°C for five days, with temperatures exceeding 55°C for at least four hours of this period. Most species of microorganisms cannot survive at temperatures above 60-65°C, so compost managers turn or aerate their systems to bring the temperature down if they begin to get this hot.

As the compost begins to cool, turning the pile usually will result in a new temperature peak because of the replenished oxygen supply and the exposure of organic matter not yet thoroughly decomposed. After the thermophilic phase, the compost temperature drops and is not restored by turning or mixing. At this point, decomposition is taken over by mesophilic microbes through a long process of "curing" or maturation. Although the compost temperature is close to ambient during the curing phase, chemical reactions continue to occur that make the remaining organic matter more stable and suitable for use with plants.

**Mechanisms of Heat Loss**

The temperature at any point during composting depends on how much heat is being produced by microorganisms, balanced by how much is being lost through conduction, convection, and radiation. Through *conduction*, energy is transferred from atom to atom by direct contact; at the edges of a compost pile, conduction causes heat loss to the surrounding air molecules.
Convection refers to transfer of heat by movement of a fluid such as air or water. When compost gets hot, warm air rises within the system, and the resulting convective currents cause a steady but slow movement of heated air upwards through the compost and out the top. In addition to this natural convection, some composting systems use "forced convection" driven by blowers or fans. This forced air, in some cases triggered by thermostats that indicate when the piles are beginning to get too hot, increases the rates of both conductive and convective heat losses. Much of the energy transfer is in the form of latent heat -- the energy required to evaporate water. You can sometimes see steamy water vapor rising from hot compost piles or windrows.

The third mechanism for heat loss, radiation, refers to electromagnetic waves like those that you feel when standing in the sunlight or near a warm fire. Similarly, the warmth generated in a compost pile radiates out into the cooler surrounding air. The smaller the bioreactor or compost pile, the greater the surface area-to-volume ratio, and therefore the larger the degree of heat loss to conduction and radiation. Insulation helps to reduce these losses in small compost bioreactors.

Moisture content affects temperature change in compost; since water has a higher specific heat than most other materials, drier compost mixtures tend to heat up and cool off more quickly than wetter mixtures, providing adequate moisture levels for microbial growth are maintained. The water acts as a kind of thermal flywheel, damping out the changes in temperature as as microbial activity ebbs and flows.

Other Physical Factors

Particle Size

Microbial activity generally occurs on the surface of the organic particles. Therefore, decreasing particle size, through its effect of increasing surface area, will encourage microbial activity and increase the rate of decomposition. On the other hand, when particles are too small and compact, air circulation through the pile is inhibited. This decreases O2 available to microorganisms within the pile and ultimately decreases the rate of microbial activity.

Particle size also affects the availability of carbon and nitrogen. Large wood chips, for example, provide a good bulking agent that helps to ensure aeration through the pile, but they provide less available carbon per mass than they would in the form of wood shavings or sawdust.

Aeration

Oxygen is essential for the metabolism and respiration of aerobic microorganisms, and for oxidizing the various organic molecules present in the waste material. At the beginning of microbial oxidative activity, the O2 concentration in the pore spaces is about 15-20% (similar to the normal composition of air), and the CO2 concentration varies form 0.5-5%. As biological activity progresses, the O2 concentration falls and CO2 concentration increases. If the average O2 concentration in the pile falls below about 5%, regions of anaerobic conditions develop. Providing the anaerobic activity is kept to a minimum, the compost pile acts as a bio-filter to trap and degrade the odorous compounds produced as a by-product of anaerobic decomposition. However, should the anaerobic activity increase above a certain threshold, undesirable odors may result.

Maintaining aerobic conditions can be accomplished by various methods including drilling air holes, inclusion of aeration pipes, forced air flow, and mechanical mixing or turning. Mixing and turning increase aeration by loosening up and increasing the porosity of the compost mixture.
**Moisture**

A moisture content of 50-60% is generally considered optimum for composting. Microbially induced decomposition occurs most rapidly in the thin liquid films found on the surfaces of the organic particles. Whereas too little moisture (<30%) inhibits bacterial activity, too much moisture (>65%) results in slow decomposition, odor production in anaerobic pockets, and nutrient leaching. The moisture content of compostable materials ranges widely, as shown in the table below:

Often the same materials that are high in nitrogen are very wet, and those that are high in carbon are dry. Combining the different kinds of materials yields a mix that comports well. You can calculate the optimal mix of materials or use the less precise "squeeze test" to gauge moisture content. (Using the squeeze test, the compost mixture should feel damp to the touch, with about as much moisture as a wrung-out sponge.)

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture Content (percent)</th>
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<tbody>
<tr>
<td>Peaches</td>
<td>80</td>
</tr>
<tr>
<td>Lettuce</td>
<td>87</td>
</tr>
<tr>
<td>Dry dog food</td>
<td>10</td>
</tr>
<tr>
<td>Newspaper</td>
<td>5</td>
</tr>
</tbody>
</table>

**Size and Shape of Compost System**

A compost pile must be of sufficient size to prevent rapid dissipation of heat and moisture, yet small enough to allow good air circulation. A minimum of 10 gallons is required for experimental systems in garbage cans if heat build-up is to occur within a few days. Smaller systems can be used for classroom research or demonstration projects but will require insulation for heat retention.

The shape of the pile helps to control its moisture content. In humid regions, outdoor compost systems may need to be sheltered from precipitation; in arid regions, piles should be constructed with a concave top to catch precipitation and any other added water.