The Science and Engineering of Composting

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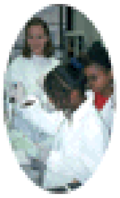
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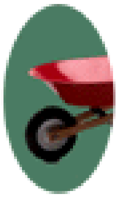
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A Note to Casual Composters

Composting can be pursued at many different levels, from the gardener who likes to produce "black gold" to the operator of a multi-acre commercial composting facility. Gardeners who compost their own landscaping and food scraps can follow a few simple rules of thumb and needn't worry about complex formulas, chemical equations, or studies of microorganisms. These are, however, important considerations for municipal and commercial composting operations because of the need to ensure that the composting proceeds rapidly, doesn't cause odor or pest problems, and achieves temperatures high enough to kill pathogens.

Some of the topics in the Science and Engineering section may be far too technical to be relevant to casual composters. On the other hand, some may be intriguing. You might, for example, wish to learn more about the invertebrates or the microorganisms that create compost. You might be curious about the temperature curve produced by compost as it goes through its cycle of heating and cooling. Or you might like to learn how to measure the pH or moisture content of your compost. You might even want to try calculating desirable proportions for the materials you wish to compost.

We invite you to explore these pages to whatever level your curiosity takes you, realizing that compost is a rich topic for scientific research and discovery as well as a practical method of recycling organic matter and reducing solid waste.

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Invertebrates of the Compost Pile

There is a complex food web at work in a compost pile, representing a 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

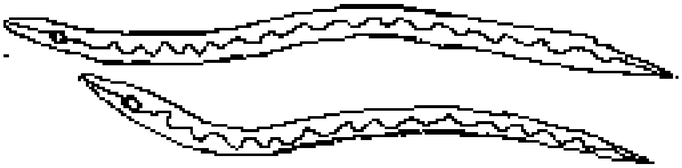
Secondary Consumers
(organisms that eat primary consumers)
springtails, some types of mites, feather-winged beetles
nematodes, protozoa, rotifera, soil flatworms

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 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.

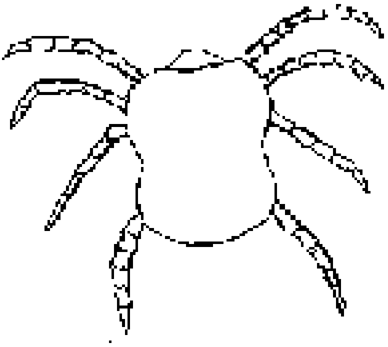
Many kinds of worms, including earthworms, nematodes, red worms and potworms eat decaying vegetation and microbes and excrete organic compoundss that enrich compost. Their tunneling aerates the compost, and their feeding increases the surface area of organic matter for microbes to act upon. As each decomposer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

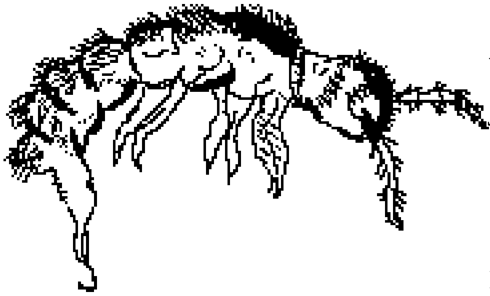


Nematodes: These tiny, cylindrical, often transparent microscopic worms are the most abundant of the physical decomposers - a handful of decaying compost contains several million. It has been estimated that one rotting apple contains 90,000. Under a magnifying lens they resemble fine human hair.

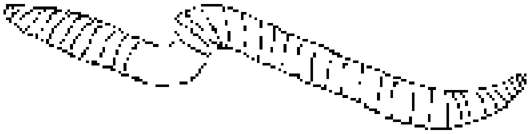
Some species scavenge on decaying vegetation, some feed on bacteria, fungi, protozoa and other nematodes, and some suck the juices of plant roots, especially root vegetables.

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.

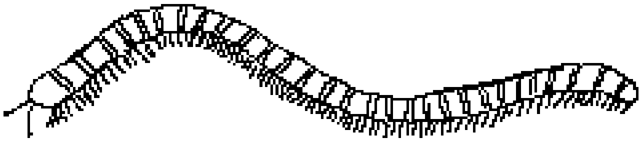


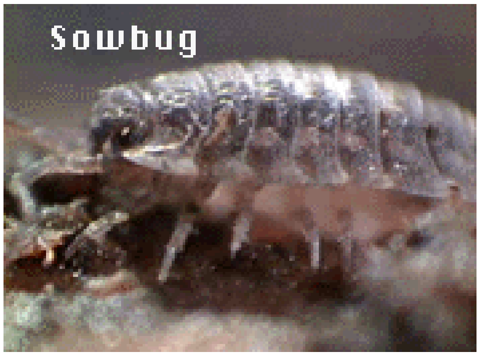
Earthworms: Earthworms do the lion's share of the decomposition work among the larger compost organisms. They are constantly tunneling and feeding on dead plants and decaying insects during the daylight hours. Their tunneling aerates the compost and enables water, nutrients and oxygen to filter down. "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 (right): 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. **To view a QuickTime movie of the centipede click on this image**

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.





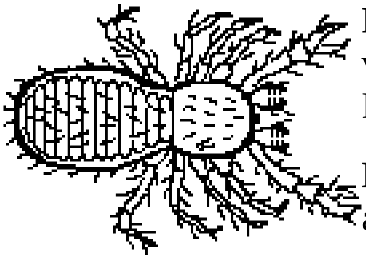
Sow Bugs (right): Sow Bugs are fat bodied crustaceans with delicate plate-like gills along the lower surface of their abdomens which must be kept moist. They move slowly grazing on decaying vegetation.

Beetles (left): 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 honey-dew, 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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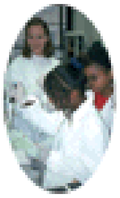

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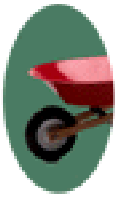

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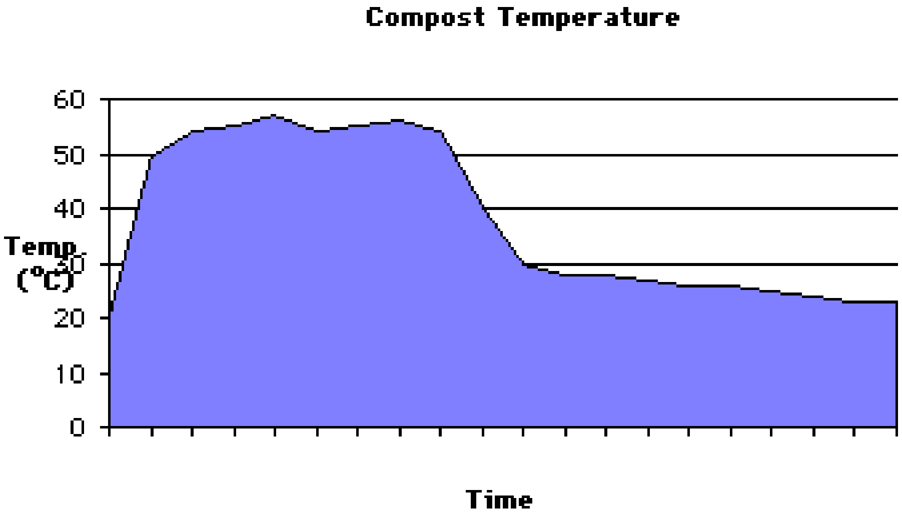
Compost Microorganisms

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.

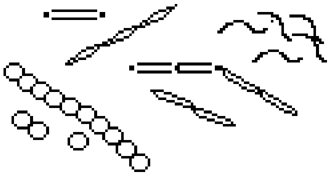


Different communities of microorganisms predominate during the various composting phases. Initial decomposition is carried out by mesophilic microorganisms, which rapidly break down the soluble, readily degradable compounds. The heat they produce causes the compost temperature to rapidly rise.

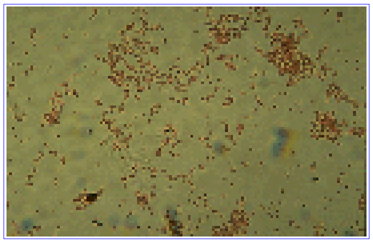
As the temperature rises above about 40°C, the mesophilic microorganisms become less competitive and are replaced by others that are thermophilic, or heat-loving. At temperatures of 55°C and above, many microorganisms that are human or plant pathogens are destroyed. Because temperatures over about 65°C 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 carboydrates 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.

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.



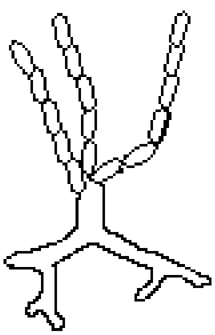
Bacteria are single-celled and structured as either rod-shaped bacilli, sphere-shaped cocci or spiral-shaped spirilla. Many are motile, meaning that they have the ability to move under their own power. At the beginning of the composting process (0-40°C), mesophilic bacteria predominate. Most of these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

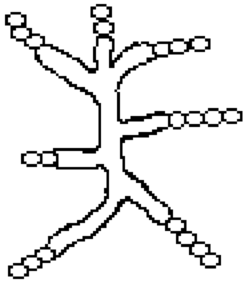
As the compost heats up above 40°C, thermophilic bacteria take over. The microbial populations during this phase are dominated by members of the genus Bacillus. The diversity of bacilli species is fairly high at temperatures from 50-55°C but decreases dramatically at 60°C or above. When conditions become 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.

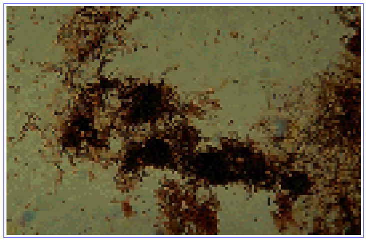
Once the compost cools down, mesophilic bacteria again predominate. The numbers and types of mesophilic microbes that recolonize compost as it matures depend on what spores and organisms are present in the compost as well as in the immediate environment. In general, the longer the curing or maturation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

Actinomycetes



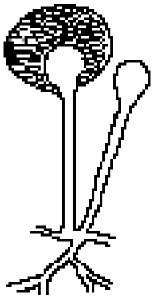


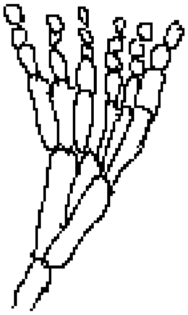
The characteristic earthy smell of soil is caused by actinomycetes, organisms that resemble fungi but actually are filamentous bacteria. Like other bacteria, they lack nuclei, but they grow multicellular filaments like fungi. In composting they play an important role in degrading complex organics such 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.

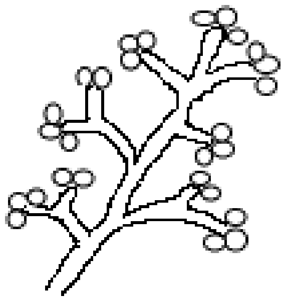


Actinomycetes form long, thread-like branched filaments that look like gray spider webs stretching through compost. These filaments are most commonly seen toward the end of the composting process, in the outer 10 to 15 centimeters of the pile. Sometimes they appear as circular colonies that gradually expand in diameter.

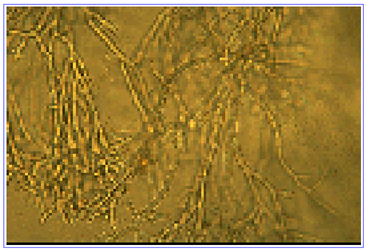
Fungi





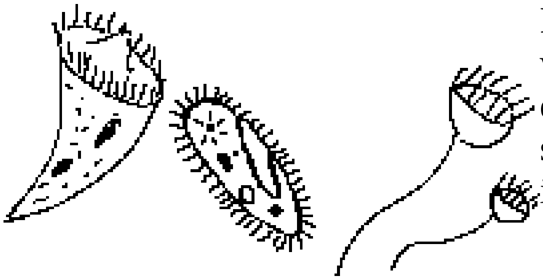


Fungi include molds and yeasts, and collectively they are responsible for the decomposition of many complex plant polymers in soil and compost. In compost, fungi are important because they break down tough debris, enabling bacteria to continue the decomposition process once most of the cellulose has 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.

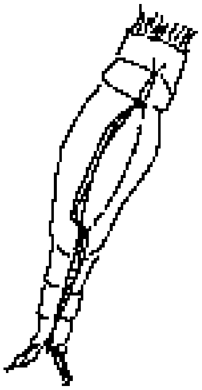
Protozoa



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 also ingest bacteria and fungi.



Techniques for Observing Compost Microorganisms

Acknowledgments

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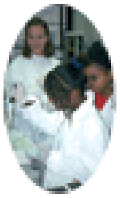

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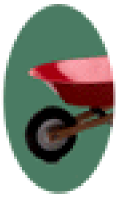

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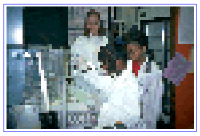
Compost Chemistry



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 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, 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.

Materials High in Carbon	C/N*
autumn leaves	30-80:1
straw	40-100:1
wood chips or sawdust	100-500:1
bark	100-130:1
mixed paper	150-200:1
newspaper or corrugated cardboard	560:1

Materials High in Nitrogen	C:N*
vegetable scraps	15-20:1
coffee grounds	20:1
grass clippings	15-25:1
manure	5-25:1

** Source: Dickson, N., T. Richard, and R. Kozlowski. 1991. Composting to Reduce the Waste Stream: A Guide to Small Scale Food and Yard Waste Composting. Available from the Northeast Regional Agricultural Engineering Service, Cornell University, 152 Riley-Robb Hall, Ithaca, NY 14853; 607-255-7654.*

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.

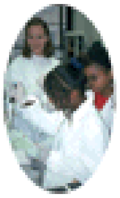
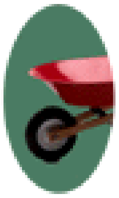
Nutrient Balance

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.

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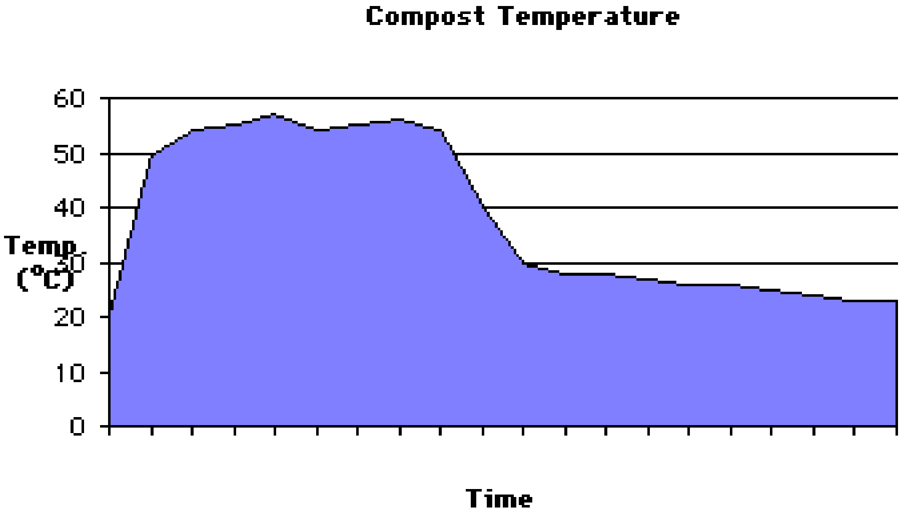
Compost Physics

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, undesireable 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:

Material	Moisture (wet basis)
Peaches	80%
Lettuce	87%
Dry dog food	10%
Newspaper	5%

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 composts 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.)

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.

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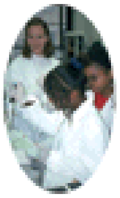

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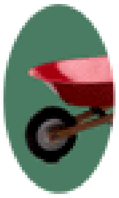

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Written by Nancy Trautmann, Cornell Center for the Environment

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Credits -->

Getting the Right Mix
Calculations for Thermophilic Composting

Tom L. Richard and Nancy M. Trautmann

One of the first tasks in developing a successful composting program is getting the right combination of ingredients. Two parameters are particularly important in this regard: moisture content and the carbon to nitrogen (C/N) ratio.

Moisture is essential to all living organisms, and most microorganisms, lacking mechanisms for moisture retention (like our skin), are particularly sensitive in this regard. Below a moisture content of 35 to 40%, decomposition rates are greatly reduced; below 30% they virtually stop. Too much moisture, however, is one of the most common factors leading to anaerobic conditions and resulting odor complaints. The upper limit of moisture varies with different materials, and is a function of their particle sizes and structural characteristics, both of which affect their porosity. For most compost mixtures, 55 to 60% is the recommended upper limit for moisture content. Because composting is usually a drying process (through evaporation due to microbially generated heat), starting moisture contents are usually in this upper range.

Of the many elements required for microbial decomposition, carbon and nitrogen are both the most important and the most commonly limiting (occasionally phosphorous can also be limiting). Carbon is both an energy source (note the root in our word for high energy food: carbohydrate), and the basic building block making up about 50 percent of the mass of microbial cells.

Nitrogen is a crucial component of proteins, and bacteria, whose biomass is over 50% protein, need plenty of nitrogen for rapid growth. When there is too little nitrogen, the microbial population will not grow to its optimum size, and composting will slow down. In contrast, too much nitrogen allows rapid microbial growth and accelerates decomposition, but this can create serious odor problems as oxygen is used up and anaerobic conditions occur. In addition, some of this excess nitrogen will be given off as ammonia gas that generates odors while allowing valuable nitrogen to escape. Therefore, materials with a high nitrogen content, such as fresh grass clippings, require more careful management to insure adequate oxygen transport, as well as thorough blending with a high carbon waste. For most materials, a C/N ratio of about 30 to 1 (by weight) will keep these elements in approximate balance, although several other factors can also come into play.

So, if you have several materials you want to compost, how do you figure out the appropriate mix to achieve moisture and C/N goals? The theory behind calculating mix ratios is relatively simple - high school algebra is the only prerequisite. To help you understand these equations, and calculate the right mix for your situation, we developed a set of informative pages, on-line calculations, and spreadsheets you can download and operate anytime with software on your own computer. You can access this material directly from the Cornell Composting Science and Engineering page, or by clicking on one of the items below:

Moisture Content
Carbon/Nitrogen Ratios

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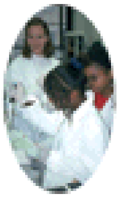

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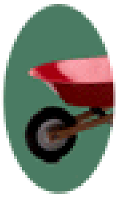

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Moisture Content

by Nancy Trautmann and Tom Richard

When deciding what proportions of various materials to mix together in making compost, the moisture of the resulting mixture is one of the critical factors to consider. The following steps outline how to design your intital mix so that it will have a suitable moisture level for optimal composting.

1. Calculate the % moisture for each of the materials you plan to compost.
   a) Weigh a small container.
   b) Weigh 10 g of the material into the container.
   c) Dry the sample for 24 hours in a 105-110&degree;C oven.
   d) Reweigh the sample, subtract the weight of the container, and determine the moisture content using the following equation:

   $M_n = ((W_w - W_d)/W_w) \times 100$
   in which:
   M_n = moisture content (%) of material n
   W_W = wet weight of the sample, and
   W_d = weight of the sample after drying.

   Suppose, for example, that you weigh 10 g of grass clippings (W_w) into a 4 g container and that after drying the container plus clippings weighs 6.3 g. Subtracting out the 4-g. container weight leaves 2.3 g as the dry weight (W_d) of your sample. Percent moisture would be:

   $M_n = ((W_w - W_d)/W_w) \times 100$
   $= ((10 - 2.3) / 10) \times 100$
   = 77% for the grass clippings
2. Choose a moisture goal for your compost mixture. Most literature recommends a moisture content of 50%-60% by weight for optimal composting conditions.
3. The next step is to calculate the relative amounts of materials you should combine to achieve your moisture goal. The general formula for percent moisture is:

$$G = \frac{(Q_1 \times M_1) + (Q_2 \times M_2) + (Q_3 \times M_3) + \ldots}{Q_1 + Q_2 + Q_3 + \ldots}$$

in which:
Q_n = mass of material n ("as is", or "wet weight")
G = moisture goal (%)
M_n = moisture content (%) of material n

You can use this formula directly to calculate the moisture content of a mixture of materials, and try different combinations until you get results in a reasonable range. If you have a browser capable of handling Java script (e.g. Netscape version 2.0 or higher), you can try this formula out for up to 3 materials.

Using trial and error to determine what proportions to use for a mixture will work, but there is a faster way. For two materials, the general equation can be simplified and solved for the mass of a second material (Q_2) required in order to balance a given mass of the first material (Q_1). Note that the moisture goal must be **between** the moisture contents of the two materials being mixed.

$$Q_2 = \frac{(Q_1 \times G) - (Q_1 \times M_1)}{M_2 - G}$$

For example, suppose you wish to compost 10 kg grass clippings (moisture content = 77%). In order to achieve your moisture goal of 60% for the compost mix, you calculate the mass of leaves needed (moisture content = 35%):

$$Q_2 = \frac{(Q_1 \times G) - (Q_1 \times M_1)}{M_2 - G}$$

Q_2= ((10 kg)(60) - (10 kg)(77)) / (35 - 60)
= 6.8 kg leaves

Mixtures of 3 or more materials can also be solved in a similar way (although the algebra is more complicated), but for an exact solution the amounts of all but one material must be specified. To find the mass of the third material (Q_3) given the masses of the first two (Q_1 and Q_2) plus all three moisture contents (M_1, M_2, and M_3) and a goal (G), solve:

$$Q_3 = \frac{(G \times Q_1) + (G \times Q_2) - (M_1 \times Q_1) - (M_2 \times Q_2)}{M_3 - G}$$

With an internet browser that incorporates the JavaScript language, you can try calculating **mixtures ratios based on moisture goals** for up to three materials.

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C/N Ratio

Tom Richard and Nancy Trautmann

Once you have calculated the moisture content of your compost mixture, the other important calculation is the carbon-to-nitrogen ratio (C/N). Grass clippings and other green vegetation tend to have a higher proportion of nitrogen (and therefore a lower C/N ratio) than brown vegetation such as dried leaves or wood chips. If your compost mix is too low in nitrogen, it will not heat up. If the nitrogen proportion is too high, the compost may become too hot, killing the compost microorganisms, or it may go anaerobic, resulting in a foul-smelling mess. The usual recommended range for C/N ratios at the start of the composting process is about 30/1, but this ideal may vary depending on the bioavailability of the carbon and nitrogen. As carbon gets converted to CO2 (and assuming minimal nitrogen losses) the C/N ratio decreases during the composting process, with the ratio of finished compost typically close to 10/1.

Typical C/N ratios and nitrogen values for many kinds of compostable substances can be looked up in published tables such as Appendix A, On-Farm Composting Handbook. Some additional nitrogen and ash data is in the table of Lignin and Other Constituents of Selected Organic Materials. (A No-Frames version of the Table of Lignin is also available.) To calculate the carbon content given C/N and percent nitrogen, solve:

%C = %N x C/N

You may be able to measure the carbon and nitrogen content of your own materials and then calculate the ratio directly. Soil nutrient analysis laboratories or environmental testing laboratories can do the nitrogen test, and maybe carbon as well . Your local Cooperative Extension office can give you the names of soils laboratories in your area. The Cornell Nutrient Analysis Lab has information about their procedures for total carbon, organic carbon, and total nitrogen analysis. You can also estimate the carbon content from ash or volatile solids data if either is available. Once you have the C/N ratios for the materials you plan to compost, you can use the following formula to figure out the ratio for the mixture as a whole:

$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3) + \ldots}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3) + \ldots}$$

in which:

R = C/N ratio of compost mixture
Qn = mass of material n ("as is", or "wet weight")
Cn = carbon (%) of material n
Nn = nitrogen (%) of material n
Mn = moisture content (%) of material n

This equation can also be solved exactly for a mixture of two materials, knowing their carbon, nitrogen, and moisture contents, the C/N ratio goal, and specifying the mass of one ingredient. By simplifying and rearranging the general equation, the mass of the second material required would be:

$$Q_2 = \frac{Q_1 \times N_1 \times \left(R - \frac{C_1}{N_1}\right) \times (100 - M_1)}{N_2 \times \left(\frac{C_2}{N_2} - R\right) \times (100 - M_2)}$$

Returning to the previous example of grass and leaves, lets assume the nitrogen content of the grass is 2.4% while that of the leaves is 0.75%, and the carbon contents are 45% and 50% respectively. Simple division shows us that the C/N ratio of the grass is 18.75 and the C/N content of the leaves is 66.67% For the same 10 kg of grass we had before, if our goal is a C/N ratio of 30:1, the solution is:

$$Q_2 = \frac{10 \times 2.4 \times (30 - 18.75) \times (100 - 77)}{0.75 \times (66.67 - 30) \times (100 - 35)}$$

$$= 3.5 \text{ kg}$$

Note that we need only 3.5 kg leaves to balance the C/N ratio, compared with 6.8 kg leaves needed to achieve the 60% moisture goal according to our previous moisture calculation. If the leaves were wetter or had a higher C/N ratio, the difference would be even greater. So how many leaves should you add?

If we solve the general form of the C/N equation for the 10 kg of grass and the 6.8 kg of leaves (determined from the moisture calculation), and use the same values for percent moisture, C, and N, the resulting C/N ratio is a little less than 37:1. In contrast, if we solve the general form of the moisture equation for 10 kg of grass and only 3.5 kg of leaves, we get a moisture content over 66%. (To gain familiarity with using the equations, you can check these results on your own).

In this example, as is often the case, moisture is the more critical variable. This is especially true toward the wet end of the optimum (>60%), where anaerobic conditions are likely to result. So it is usually best to err on the side of a high C/N ratio, which may slow down the compost a bit but is more likely to be trouble free. If, on the other hand, your mixture is dry, then you should optimize the C/N ratio and add water as required.

As with moisture calculations, mixtures of 3 or more materials can be solved for the mass of the third material if the first two are specified (one equation & one unknown). Given the carbon, nitrogen and moisture contents of each ingredient, the masses of the first two, and the C/N ratio goal, the solution for the mass of the third material is:

$$Q_3 = \frac{RQ_1N_1(100-M_1)+RQ_2N_2(100-M_2)-Q_1C_1(100-M_1)-Q_2C_2(100-M_2)}{C_3(100-M_3)-RN_3(100-M_3)}$$

If we also want to consider moisture content, we can solve both equations simultaneously (moisture and C/N) for any two unknowns.


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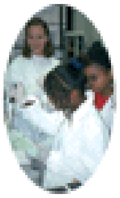
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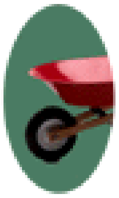
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Bioavailability of Carbon and Nitrogen

Tom Richard

Carbon-to-nitrogen ratios may need to be adjusted depending on the bioavailability of these elements. This is commonly an issue with high carbon materials, which are often derived from wood and other lignified plant materials, as increased lignin content reduces biodegradability. Particle size is also an important factor, with smaller particles degrading more quickly than large particles of the same material. Bioavailability can also be a factor with nitrogen sources, especially fertilizer nitrogen, where nearly instant availability can exceed the assimilative capacity of the microbial community and be lost as ammonia odors and nitrate in leachate.

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Use of Fertilizer Nitrogen to balance C/N Ratios

Tom Richard

When composting high carbon materials such as leaves, additional nitrogen may be required to reduce the C/N ratio to the optimal range. If considering using fertilizer as an N source, one needs to proceed cautiously. While the theoretical number should be the same as calculated using the C/N ratio formulas, the nitrogen in fertilizers is released much more rapidly than that in organic nitrogen (from which the rules of thumb are derived).

Organic nitrogen sources provide a natural "time release" that makes them available at a rate comparable to the growth rate of microorganisms in the compost, so they are utilized efficiently. The rapid availability of nitrogen fertilizers is especially a concern in the fall and winter, when low temperatures slow down the growth rate of microorganisms, and nitrogen uptake will be correspondingly slow. To mimic a natural time release with synthetic fertilizers, they should be applied sparingly and in a series of applications. While there is not a research base on which to estimate what the right rate would be, sniffing for ammonia volatilization may indicate if too much was applied too soon. In addition, because none of the fertilizer nitrogen is locked into compounds that are difficult to degrade (as is the case with organic sources), the total applied should be significantly less than the calculations indicate - perhaps half to two thirds.


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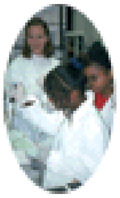
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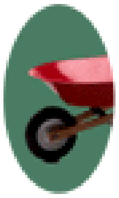
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The Effect of Lignin on Biodegradability

Tom Richard

Plant cell wall material is composed of three important constituents: cellulose, lignin, and hemicellulose. Lignin is particularly difficult to biodegrade, and reduces the bioavailability of the other cell wall constituents. A bit of knowledge about each of these constituents is helpful in understanding the vastly different rates that different plant materials decompose. This discussion also presents the mathematical models developed to compensate for the effect of lignin on biodegradability in anaerobic systems, and suggests some constraints on applying these models to aerobic composting systems.

Cell Wall Constituents

Cellulose is a long chain of glucose molecules, linked to one another primarily with $\beta(1\text{-}4)$ glycosidic bonds. The simplicity of the cellulosic structure, using repeated identical bonds, means that only a small number of enzymes are required to degrade this material. Although people do not produce the enzymes required for cellulose degradation (and thus do not get much energy from eating paper, straw or other cellulosic material), some microorganisms do. Cows and other ruminants create an environment in their rumen which encourages this microbial degradation, converting cellulose to volatile fatty acids and microbial biomass which the ruminant can then digest and use.

Hemicelluloses are branched polymers of xylose, arabinose, galactose, mannose, and glucose. Hemicelluloses bind bundles of cellulose fibrils to form microfibrils, which enhance the stability of the cell wall. They also cross-link with lignin, creating a complex web of bonds which provide structural strength, but also challenge microbial degradation (Ladisch et al., 1983; Lynch, 1992).

Lignin is a complex polymer of phenylpropane units, which are cross-linked to each other with a variety of different chemical bonds. This complexity has thus far proven as resistant to detailed biochemical characterization as it is to microbial degradation, which greatly impedes our understanding of its effects. Nonetheless, some organisms, particularly fungi, have developed the necessary enzymes to break lignin apart. The initial reactions are mediated by extracellular lignin and manganese peroxidases, primarily produced by white-rot fungi (Kirk and Farrell, 1987. Actinomycetes can also decompose lignin, but typically degrade less than 20 percent of the total lignin present (Crawford, 1986; Basaglia et al., 1992). Lignin degradation is primarily an aerobic process, and in an anaerobic environment lignin can persist for very long periods (Van Soest, 1994).

Because lignin is the most recalcitrant component of the plant cell wall, the higher the proportion of lignin the lower the bioavailability of the substrate. The effect of lignin on the bioavailability of other cell wall components is thought to be largely a physical restriction, with lignin molecules reducing the surface area available to enzymatic penetration and activity (Haug, 1993).

Modeling Lignin's Impacts on Biodegradability in Anaerobic Systems

Chandler et al. (1980) formulated a mathematical correction for bioavailability of an organic substrate based on its lignin content. Using data collected from the anaerobic degradation of a range of lignocellulosic materials (40 day retention time), they developed a linear relationship to describe this effect:

$$\text{Biodegradable fraction} = 0.83 - \left(0.028 \times \text{lignin}_{\%\,VS}\right)$$

where

$$\text{lignin}_{\%\,VS} = \frac{\text{lignin}_{\%}}{VS_{\%}\ /100} = \text{ lignin content as a percent of volatile solids}$$

$\text{lignin}_{\%}$ = the lignin content as a percent of total solids

$VS_{\%}$ = volatile solids as a percent of total solids

Kayhanian and Tchobanoglous (1992) proposed using this equation to adjust C/N ratios for mixture calculations in a sequenced anaerobic / aerobic process. The effect, for highly lignified materials, can be significant. For example, using their lignin data for newspaper versus office paper:

Material	Lignin Content (% of VS)	Biodegradable fraction of VS
Newsprint	21.9	0.217
Office paper	O.4	0.819

Thus, while about 82% of the carbon in office paper is biodegradable, only 22% of the carbon in newsprint would be available through anaerobic digestion. Put another way, it would take almost 4 tons of newsprint amendment to provide the same bioavailable carbon as 1 ton of office paper. This clearly has significant implications for mixture ratio calculations.

Further evaluation of Chandler et al.'s (1980) relationship compared the predicted biodegradability with long term (75 day) batch studies in a high-solids anaerobic digestor (Kayhanian, 1995). The predicted biodegradability of this solid waste mixture based on its lignin content (typically 4%) was 68%, which was comparable to the 70% biodegradability measured in the long term batch study.

The linear relationship given by Chandler et al. (1980) is simple, and appears to provide reasonable accuracy for materials of relatively low lignin content. While Chandler et al.'s relationship makes mechanistic sense for relatively small lignin fractions, materials with a high lignin content may be affected differently. With a large amount of lignin present, some of the lignin would be overlapping other lignin molecules rather than cellulose, so the incremental effect will be smaller(Conrad et al., 1984). Recent analysis of extensive databases on the maximum digestibility of lignocellulosic materials in the rumen suggests a log-linear relationship provides a better fit (Van Soest, 1996):

$$\text{digestable fraction of cell wall} = 100 - 5.41\left(\text{lignin}_{\%\,\text{cell wall}}\right)^{0.76}$$

where

cell wall = approximately the sum of cellulose, hemicellulose, and lignin. Plant cell wall is also called Neutral Detergent Fiber (so named for the analytical procedure used).

$$\text{lignin}_{\%\,\text{cell wall}} = \left(\frac{\text{lignin}_{\%}}{\text{cell wall}_{\%}/100}\right) = \text{lignin as a percent of plant cell wall, and}$$

$$\text{cell wall}_{\%} = \text{cell wall as a percent of total solids}$$

Applying the formula of Van Soest (1996) to the cell wall fraction, we can calculate an overall biodegradable carbon content:

$$C_{\text{biodegradable}} = C_{\text{total}}\left(\frac{\text{cell wall}_{\%}}{100}\right)\left(1 - 0.0541\left(\text{lignin}_{\%\,\text{cell wall}}\right)^{0.76}\right) + C_{\text{total}}\left(1 - \frac{\text{cell wall}_{\%}}{100}\right)$$

This biodegradable carbon content can then be used to calculate biodegradable C/N ratios using the usual formulas. If we apply this equation to newsprint, wheat straw, maple wood chips and poultry manure, using data from the Table of Lignin and Other Constituents of Selected Organic Materials and other sources, we get the following biodegradable C/N ratios (access a No-Frames version of the Table of Lignin here):

Material	**Carbon (%) (Total)**	**C/N (Total)**	**Carbon (%) (biodegradable)**	**C/N (biodegradable)**	**Lignin (%) (dry basis)**	**Cell wall (%) (dry basis)**	**Nitrogen (%) (dry basis)**
newsprint	39.3	115.5	18.4	54.2	20.9	97.0	0.34
wheat straw	51.1	88.7	33.6	58.4	23.0	95.0	0.58
manure, poultry	43.3	9.6	41.8	9.3	2.0	38.0	4.51
wood chips, maple	49.7	51.2	43.8	45.1	12.7	32.0	0.97

Note, however, that when correcting carbon/nitrogen ratio calculations for lignin content, it may also be necessary to reduce the carbon/nitrogen goal. The typical recommended C/N ratio of 30:1 must presumably already include some discount for lignin, which is a component of most common carbonaceous materials.

It is also important to remember that these formulas are all based on data from anaerobic systems. Since lignin is degradable (albeit slowly) in aerobic systems, the restriction on biodegradability will be less in aerobic composting.

Lignin degradation under aerobic conditions

There is some debate and perhaps significant variability in the rate of lignin decomposition in aerobic systems. Lynch and Wood (1985) state that "little, if any, lignin degradation occurs during composting", and Iiyama et al. (1995) assume constant lignin as the basis of their calculations of polysaccharide degradation. However, Hammouda and Adams (1989) measured lignin degradation ranging from 17% to 53% in grass, hay and straw during 100 days of composting, and Tomati et al. (1995) measured a 70% reduction in the lignin content of olive waste compost after 23 days under high moisture (65-83%) thermophillic conditions. Interestingly, after this initially high decomposition rate under thermophillic conditions, Tomati et al. found no further reductions in lignin content during the subsequent 67 days under mesophillic conditions. In contrast, in a laboratory incubation study, Horwath et al. (1995) measured 25% lignin degradation during mesophillic composting and 39% during thermophillic composting of grass straw during 45 day experiments.

Adding small quantities of nitrogen to woody materials can increase lignin degradation rates. Over a two week incubation with a white-rot fungi at 39-40°C (the optimum temperature for growth of *Phanerochaete chrysosporium*, the fungi used in this experiment), adding only 0.12% nitrogen (dry weight basis), lignin degradation in alder pulp increased from 5.2% to 29.8% (Yang et al., 1980). In this same study, the increase in lignin degradation of hemlock pulp with 0.12% supplemental nitrogen was only 2.2% to 3.9%, and additional nitrogen did not provide further benefit. The differences between plant species is likely related to differences in lignin structure, with gymnosperm lignin composed of coniferyl alcohols, angiosperm lignin composed of both coniferyl and sinapyl alcohols, and grass lignin of coniferyl, sinapyl, and p -coumaryl alcohols (Ladisch et al., 1983).

While significant lignin degradation appears possible during aerobic composting, a number of factors are likely to affect the decomposition rate. Conditions which favor the growth of white-rot fungi, including adequate nitrogen, moisture, and temperature, all appear to be important in encouraging lignin decomposition, as does the composition of the lignocellulosic substrate itself.

The impact of lignin degradation on the biodegradability of the remaining carbon has not been extensively researched. In one of the few studies which might provide such insight, Latham (1979) measured a 5 to 11% increase in anaerobic digestability of barley straw after 3 to 4 week aerobic incubations at 30°C with various pure cultures of white-rot fungal species. Increases in biodegradability would likely be even greater with a mixed culture under themophillic conditions, as evidenced by the lignin degradation rates cited above.

Pretreatment to enhance biodegradability

Biodegradability can be enhanced by pretreatment of lignocellulosic materials, including acid (Grethelin, 1985) or alkali treatment (Jackson, 1977; Van Soest, 1994), ammonia and urea (Basaglia et al., 1992; Van Soest, 1994), physical grinding and milling (Ladisch et al., 1983; Fahey et al, 1992), fungal degradation and steam explosion (Sawada et al, 1995), and combined alkali and heat treatment (Gossett et al., 1976). Gharpuray et al. (1983) examined several of these pretreatment options individually and in combination, and found that those treatments which enhanced specific surface area were most effective at increasing enzymatic hydrolysis.

While pretreatment may be uneconomical when considered as a separate process in compost feedstock preparation, in some cases it may be incorporated in other preprocessing operations at little additional cost. However, because many lignocellulosic ingredients in composting serve dual roles as energy sources and porosity enhancers, treatments which reduce porosity and pore size distributions may prove counterproductive to maintaining an aerobic process.

Summary and Conclusions

Researchers have developed quantitative relationships between lignin content and the biodegradability of lignocellulosic materials during anaerobic digestion. However, before applying these formulas to aerobic composting other factors should be considered. Several studies indicate significant biodegradation of lignin can occur during composting, which would increase the availability of other plant cell wall materials. Bioavailability will also be affected by particle size and other factors for which no quantitative correction presently exists. When analyzing aerobic composting systems, the mathematical relationships developed by Chandler et al. (1980) and Van Soest (1996) are best used in a comparative sense, to help understand the differences in bioavailability of different composting substrates.

Acknowledgment

Martin Traxler provided very helpful discussions and comments during the creation of this document.

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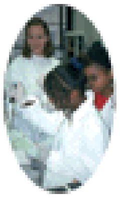

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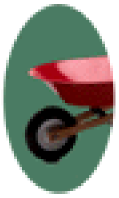

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Lignin and Other Constituents of Selected Organic Materials

Substrate	Lignin	Cell Wall	Lignin/cell wall	Crude Protein	Cell Soluble	
Wheat straw	8.9	77.1	11.6	9.3	22.9	
Corn stalks	3.9	49.6	7.8	6.6	50.4	
Corn leaves	3.8	59.3	6.5	19.0	40.7	
Cattails	8.5	63.5	13.4	13.6	36.5	
Treated kelp	6.0	33.2	18.1	30.0	66.8	
Water hyacinth	8.7	60.1	14.5	17.7	39.9	
Corn meal	2.0	21.6	9.1	11.1	78.4	
Newsprint	20.9	88.7	23.6	5.1	11.3	
Elephant m.	10.4	77.4	13.5	7.0	22.6	
Chicken m.	3.4	454.2	7.5	33.9	54.8	
Pig m.	2.2	40.5	5.4	27.6	59.5	
Cow m.	8.1	57.1	14.1	19.4	42.9	
Cow m.	7.9	52.3	15.1	20.1	47.7	
Cow m.	10.1	62.9	16.1	17.2	37.1	
Pin cherry	8.98	26.2	34.3	1.77		
Yellow birch	12.0	42.5	28.2	1.42		
Sugar maple	8.49	32.5	26.1	0.97		
Beech	12.7	61.5	20.7	1.55		


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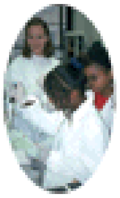
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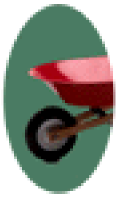
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The Effect of Particle Size on Bioavailability

Tom Richard

Decomposition occurs primarily on or near the surfaces of particles, where oxygen diffusion into the aqueous films covering the particle is adequate for aerobic metabolism, and the substrate itself is readily accessible to microorganisms and their extracellular enzymes. Small particles have more surface area per unit mass or volume than large particles, so if aeration is adequate small particles will degrade more quickly. Experiments have shown that the process of grinding compost materials can increase the decomposition rate by a factor of two (Gray and Sherman, 1970). Gray et al. (1971) recommend a particle size of 1.3 to 7.6 cm (0.5 to 2 inches), with the lower end of this scale suitable for forced aeration or continuously mixed systems, and the upper end for windrow and other passively aerated systems.

A theoretical calculation by Haug (1993) suggests that for particles larger than 1 mm in thickness, oxygen may not diffuse all the way into the center of the particle. Thus the interior regions of large particles are probably anaerobic, and decomposition rates in this region are correspondingly slow. However, anaerobic conditions are more of a problem with small particles, as the resulting narrow pores readily fill with water due to capillary action. These issues are addressed more fully in the section on factors leading to anaerobic conditions.

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Estimating Carbon content

Tom Richard

If you know the nitrogen content for an ingredient, but not the carbon content or the C/N ratio, you can estimate the % C based on the volatile solids content if that value is known or can be measured. Volatile Solids (VS) are the components (largely carbon, oxygen, and nitrogen) which burn off an already dry sample in a laboratory furnace at 500-600°C, leaving only the ash (largely calcium, magnesium, phosporus, potassium, and other mineral elements that do not oxidize). For most biological materials the carbon content is between 45 to 60 percent of the volatile solids fraction. Assuming 55 percent (Adams et al., 1951), the formula is:

% Carbon = (% VS) / 1.8
where % VS = 100 - % Ash

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Solving the Moisture and Carbon-Nitrogen Equations Simultaneously

Tom Richard

In high school algebra we learn that for any number of independent equations we can usually solve for that same number of unknowns. In this case we have two equations (one for moisture and one for the carbon-nitrogen ratio), and we can solve them for any two unknowns. Normally we use this approach to develop a mix ratio of several different ingredients, knowing the moisture, carbon, and nitrogen contents of each. If we specify the quantities of all but two ingredients, and the C/N and moisture content we'd like to achieve in the mixture, we can solve for those two remaining quantities to get the mix we want.

In selecting which material quantities to specify and which to solve for as unknowns, it is important to use a little common sense. If your moisture goal is 60%, and you are trying to compost wet leaves, sawdust, grass, and food scraps, it would be smart to make sawdust one of the unknown quantities, since all the other materials are likely to have moisture contents greater than 60%. There is no way to bring the moisture content of a mix down by adding more of a wet ingredient, and, similarly, there is no way to bring the C/N ratio up by adding high nitrogen materials.

Another useful tip, particularly for dry ingredients, is to include water as one of the unknowns. Water will bring up the moisture content without altering the C/N ratio. And since water is cheap and usually readily available, it can be an easy way to develop an appropriate mix.

The solution can be obtained in a number of ways using linear algebra or matrices. With patience, one can use simple algebraic methods to solve the moisture equation for one of the unknown quantities, and then substitute that value in the C/N equation and solve the C/N equation for the other unknown. At that point, back-substitution into the solution of the moisture equation gives both unknowns in terms of known values.

The algebraic manipulations required for a mixture of three materials are fairly straightforward but do take a little time, as is evident from the solution below.

The three ingredient equation for moisture is:

$$G = \frac{M_1 \times Q_1 + M_2 \times Q_2 + M_3 \times Q_3}{Q_1 + Q_2 + Q_3}$$

in which:

Qn = mass of material n ("as is", or "wet weight")
G = moisture goal (%)
Mn = moisture content (%) of material n

and the three ingredient equation for C/N ratio is:

$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3)}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3)}$$

in which:

R = goal (C/N ratio)
Cn = carbon (%)
Nn = nitrogen (%)
and Mn and Qn are as previously defined

The resulting solutions are:

$$Q_2 = \frac{A}{B} \quad and \quad Q_3 = \frac{C}{B}$$

where:

A = Q1 (M1 C3 (100 - M3) - M1 R N3 (100 - M3) - M3 C1 (100 - M1)
+ R N3 (100 - M3)G - R N1 (100 - M1)G +C1 (100 - M1)G
- C3 (100 - M3)G +M3 R N1 (100 - M1))

B = R N2 (100 - M2)G - R N2 (100 - M2) M3 - R N3 (100 - M3)G
+ R N3 (100 - M3)M2 - C2 (100 - M2)G + C2 (100 - M2)M3
+ C3 (100 - M3)G - C3 (100 - M3)M2

C = Q1 (R N1 (100 - M1) G - R N1 (100 - M1) M2 -R N2 (100 - M2) G
+ R N2 (100 - M2) M1 - C1 (100 -M1) G + C1 (100 - M1) M2
+ C2 (100 - M2)G - C2 (100 - M2) M1)

To see how this equation works, plug in the material characteristics from our previous example with grass and leaves, and the food scrap characteristics given below. Then solve for the quantity of leaves and/or food scraps needed to optimize C/N and moisture for 10 kg of grass.

Ingredient Characteristics:

Grass:	Q1 = 10	M1 = 77% H2O	C1 = 45% carbon	N1 = 2.4% nitrogen

Leaves:	Q2 = ?	M2 = 35% H2O	C2 = 50% carbon	N3 = 0.75% nitrogen
Food scraps:	Q3 = ?	M3 = 80% H2O	C3 = 42% carbon	N3 = 5.0% nitrogen
Mixture Goals:				
Moisture:	G = 60%			
C/N ratio:	R = 30			

A = 10 x (77 x 42 x (100 - 80) - 77 x 30 x 5.0 x (100 - 80) - 80 x 45 x (100 - 77)
+ 30 x 5.0 x (100 - 80) x 60 - 30 x 2.4 x (100 - 77) x 60 +45 x (100 - 77) x 60
- 42 x (100 - 80) x 60 +80 x 30 x 2.4 x (100 - 77))

A = -243,000

B = 30 x 0.75 x (100 - 35) x 60 - 30 x 0.75 x (100 - 35) x 80 - 30 x 5.0 x (100 - 80) x 60
+ 30 x 5.0 x (100 - 80) x 35 - 50 x (100 - 35) x 60 + 50 x (100 - 35) x 80
+ 42 x (100 - 80) x 60 - 42 x (100 - 80) x 35

B = - 18,250

C = 10 x (30 x 2.4 x (100 - 77) x 60 - 30 x 2.4 x (100 - 77) x 35
- 30 x 0.75 x (100 - 35) x 60 + 30 x 0.75 x (100 - 35) x 77 - 45 x (100 - 77) x 60
+ 45 x (100 - 77) x 35 + 50 x (100 - 35) x 60 - 50 x (100 - 35) x 77)

C = -148,625

Remembering that

$$Q_2 = \frac{A}{B} \quad \text{and} \quad Q_3 = \frac{C}{B}$$

we find that:

Q2 = 13.31 kg and Q3 = 8.14 kg

Thus if we mix 13 kg of leaves and 8 kg of food scraps with the initial 10 kg grass clippings, the mixture will achieve our goals of 60% moisture and a 30:1 C/N ratio.

Note that this simultaneous solution for three ingredients depends entirely on having the right three ingredients to combine. With many combinations the resulting Q2 and/or Q3 will be negative, indicating that no solution is possible. In that case you can add an additional material to add to the mix, such as sawdust or wood chips if the moisture or nitrogen levels are too high. Of course, if we add more ingredients, we also need a different formula to determine the solution.

For increasing numbers of materials, this formula becomes even more complicated. The solution for a mixture of four ingredients follows.

The four ingredient equation for moisture is:

$$G = \frac{M_1 \times Q_1 + M_2 \times Q_2 + M_3 \times Q_3 + M_4 \times Q_4}{Q_1 + Q_2 + Q_3 + Q_4}$$

and the four ingredient equation for C/N ratio is:

$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3) + Q_4(C_4 \times (100 - M_4)}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3) + Q_4(N_4 \times (100 - M_4)}$$

where all terms are as previously defined

If we know the carbon, nitrogen, and moisture contents of each of these materials, specify goals for moisture and C/N ratio of the mixture, and quantities of Q1 and Q2, then we can solve for Q3 and Q4. The solution is:

$Q_3 = \frac{D}{E}$ and $Q_4 = \frac{F}{E}$

where

D= -(Q1C4(100-M4)G+Q2C4(100-M4)G-Q2C2(100-M2)G-Q1C1(100-M1)G
-Q1RN4(100-M4)G-Q2RN4(100-M4)G+RQ1N1(100-M1)G+RQ2N2(100-M2)G
-M4RQ1N1(100-M1)-M1Q1C4(100-M4)+M4Q1C1(100-M1)-M2Q2C4(100-M4)
-M4RQ2N2(100-M2)+M1Q1RN4(100-M4)+M4Q2C2(100-M2)+M2Q2RN4(100-M4))

E= RN3(100-M3)G-RN3(100-M3)M4-C3(100-M3)G+C3(100-M3)M4-RN4(100-M4)G
+RN4(100-M4)M3+C4(100-M4)G-C4(100-M4)M3

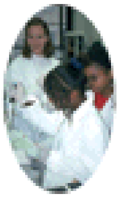
and

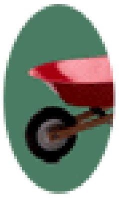
F = -RN3(100-M3)GQ1-RN3(100-M3)GQ2+RN3(100-M3)M1Q1
+RN3(100-M3)M2Q2+C3(100-M3)GQ1+C3(100-M3)GQ2
-C3(100-M3)M1Q1-C3(100-M3)M2Q2+RQ1N1(100-M1)G
-RQ1N1(100-M1)M3+RQ2N2(100-M2)G-RQ2N2(100-M2)M3
-Q1C1(100-M1)G+Q1C1(100-M1)M3-Q2C2(100-M2)G+Q2C2(100-M2)M3

This is where computers come in handy. These simultaneous solutions are included on spreadsheets you can download and use on your own computer.

Acknowledgement:

Helpful reviews of this document and the accompanying spreadsheet were provided by Nancy Trautmann.





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Compost Mixture Calculation Spreadsheets

You can download spreadsheets with built in equations to solve compost mixture calculations for up to 4 ingredients. Spreadsheets are provided in several common Macintosh and DOS/Windows formats. Use the one that is most current for your spreadsheet software. You can also ftp these files from ftp://www.cfe.cornell.edu/compost/

Note: if your spreadsheet software package is not listed, try downloading one of the earlier versions provided and importing it to your spreadsheet package.

Apple Macintosh Operating System

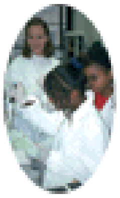
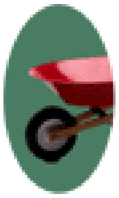
These files are compressed using Stuffit and encoded with BinHex:

- Excel for Macintosh, Version 3
- Excel for Macintosh, Version 5

Dos/Windows Operating System

- Excel, Version 3
- Excel, Version 5
- Lotus Worksheet version 1
- Lotus Worksheet version 3
- Lotus Worksheet version 4

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Ideas for Student Research Projects

Compost Ingredients

Garden supply stores and catalogs often sell compost "starters," which supposedly speed up the composting process. Develop a recipe for a compost starter and design a research project to test its effect on the compost temperature profile.

How well do human nutrition concepts apply to compost microorganisms? For example, will the microbes get a "sugar high," demonstrated by a quick, high temperature peak when fed sugary foods, compared with a longer but lower peak for more complex carbohydrates?

Measure the pH of a number of different compost mixes. How does the pH of initial ingredients affect the pH of finished compost?

Some instructions call for adding lime to increase the pH when compost ingredients are mixed. Other instructions caution to avoid this because it causes a loss of nitrogen. How does adding various amounts of lime to the initial ingredients affect the pH of finished compost?

Microorganisms

Composting recipes sometimes call for inoculating the pile by mixing in a few handfuls of finished compost. Is there any observable difference in appearance of microbes between systems that have and have not been inoculated?

Does the pH of the initial compost ingredients affect the populations of microorganisms during composting?

Compost Physics

What type of insulation works best for soda bottle bioreactors? Does it help to have a reflective layer? Do different insulative materials or different thicknesses affect the temperature profile?

When constructing compost bins or piles, some people incorporate perforated pipe, wire mesh, or other systems to increase passive air flow. What is the effect of different methods of aeration on the temperature profile of any one compost system?

How do various means and schedules for turning a pile affect the temperature profile and the time needed for production of finished compost?

What is the effect of forced aeration (with an aquarium pump or similar apparatus) on the temperature profile in a soda bottle or a two-can bioreactor?

Try mixing the same ingredients in a large outdoor pile, a two-can bioreactor, and a soda bottle bioreactor. Which system reaches the hottest temperatures? Which remains hot the longest? How does this affect the compost produced?

What is the effect of layering versus mixing organic ingredients on the compost pile temperature profile?

Worm Composting

Do organic wastes in compost break down more readily in the presence of worms than through composting that depends solely on microbial decomposition?

In some experiments, plants have not show increased growth when planted in fresh worm castings. Does aging or "curing" worm castings increase their ability to enhance plant growth? Are there chemical differences between fresh and older worm castings? Should worm compost be mixed with soil before being used to grow plants?

How do different food sources affect reproductive and growth rates of red worms (*Eisenia fetida*)?

Red worms grow best in wastes with pH between 5.0 and 8.0. How sensitive are their cocoons to pH? Will they hatch after being exposed to extreme pH? How sensitive are they to extreme drought or temperatures?

Effects of Compost on Plant Growth

Some leaves, such as those of black walnut or eucalyptus trees, contain chemicals that inhibit growth of other plants. Are these compounds broken down by composting?

Finished compost is near neutral pH. Can you design an experiment to answer one or more of the following questions: Is compost detrimental to use on acid-loving plants such as blueberries or azaleas? Does compost buffer the soil pH, making it harder to provide acidic conditions? How does it compare to peat moss in this regard?

Water in which compost has been soaked (often called compost tea) is said to be beneficial to plants. Can you design experiments to test whether different types, concentrations, and amounts of compost tea enhance plant growth?

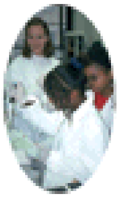
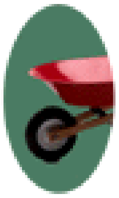
In China, farmers dig parallel trenches and fill them with organic wastes mixed with cocoons of Eisenia fetida. Soybeans planted in rows between the trenches are highly productive. Can you design and test a planting system using vermicompost?

These are a few ideas about possibilities for student research projects on composting. For more ideas, plus detailed information about techniques for carrying out composting experiments, refer to the new book, **Composting in the Classroom: Scientific Inquiry for High School Students**, by N.M.

Trautmann and M.E. Krasny. ISBN 0-7872-4433-3.

> Available from Kendall/Hunt Publishing Company at 1-800-228-0810 (US) or 1-319-589-1000 (International).

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Monitoring the Composting Process

As composting proceeds, a number of changes occur in its physical, chemical, and biological characteristics. Monitoring some of these variables will help you to assess the status of your compost and to compare the progress of systems with different initial conditions or ingredients.

- Moisture
- Temperature
- pH
- Odor
- Invertebrates
- Microbes
- Volatile Solids


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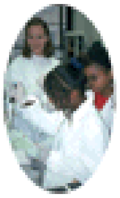
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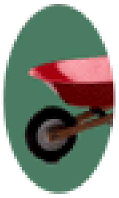
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Monitoring Compost Moisture

Composting proceeds best at a moisture content of 40-60% by weight. At lower moisture levels, microbial activity is limited. At higher levels, the process is likely to become anaerobic and foul-smelling.

When you are choosing and mixing your compost ingredients, you may wish to measure the moisture content. After the composting is underway, you probably don't need to repeat this measurement because you can observe whether appropriate moisture levels are being maintained.

If your compost starts to smell bad, chances are it's too wet. Excess water fills the pore spaces, impeding diffusion of oxygen through the compost materials and leading to anaerobic conditions. Mixing in additional bulking agent such as dry wood chips, cardboard pieces, or newspaper strips is likely to alleviate the problem. If you are composting in a bioreactor with drainage holes, you may notice leachate draining out. This liquid is often rich in nutrients and can be diluted for use on plants. You may find it useful to record the amount of leachate produced by each system, for comparison with initial moisture content, temperature curves, or other variables.

If you are blowing air through your compost system, you will need to be careful not to dry it out. If the temperature drops sooner than expected and the compost looks dry, moisture may have become the limiting factor. In this case try mixing in some water and see if the temperature rises again.


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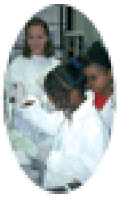
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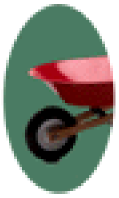
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Monitoring Compost Temperature

Temperature is one of the key indicators in composting. Is the system heating up? How hot does it get? How long does it remain hot? How does mixing affect the temperature profile?

Heat is generated as a byproduct of microbial breakdown of organic material, and you can use the temperature of your compost to gauge how well the system is working and how far along the decomposition has progressed. For example, if your compost heats up to 40 or 50C, you can deduce that the ingredients contained adequate nitrogen and moisture for rapid microbial growth.

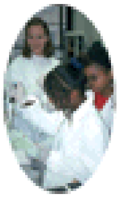
To take your temperature readings, make sure to use a probe that reaches deep into the compost. Leave the probe in place long enough for the reading to stabilize, then move it to a new location. Take readings in several locations, including at various depths from the top and sides. Compost may have hotter and colder pockets depending on the moisture content and chemical composition of ingredients. Can you find temperature gradients with depth? Where do you find your hottest readings? For systems in which air enters from the bottom, the hottest locations tend to be two-thirds or more of the way up. Is this true for your system?

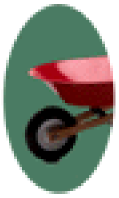
By graphing compost temperature over time, you can tell how far along the decomposition has progressed. A well constructed compost system will heat up to 40 or 50C within two to three days. As readily decomposable organic matter becomes depleted, the temperature begins to drop and the process slows considerably.

The temperature at any point depends primarily on how much heat is being produced by microorganisms and how much is lost through aeration and surface cooling. How long the system remains hot therefore depends on the chemical composition of the ingredients as well as the size and shape of the system. Moisture content also affects temperature change; 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.

You may decide to design your compost experiments to look for variables or combinations of variables that produce the highest temperatures in the shortest amount of time, or perhaps those that maintain hot temperatures for the longest period. One useful way to analyze your data might be to plot the maximum temperature and the time to reach maximum temperature for each compost system as a function of the experimental variable. For example, you could plot the maximum temperature for each system versus the percent moisture of the compost ingredients.

For more information on the science of compost temperatures, go to the Physics of Composting.





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Monitoring Compost pH

Why is compost pH worth measuring? Primarily because you can use it to follow the process of decomposition. Compost microorganisms operate best under neutral to acidic conditions, with pH's in the range of 5.5 to 8. During the initial stages of decomposition, organic acids are formed. The acidic conditions are favorable for growth of fungi and breakdown of lignin and cellulose. As composting proceeds, the organic acids become neutralized, and mature compost generally has a pH between 6 and 8.

If anaerobic conditions develop during composting, organic acids may accumulate rather than break down. Aerating or mixing the system should reduce this acidity. Adding lime (calcium carbonate) generally is not recommended because it causes ammonium nitrogen to be lost to the atmosphere as ammonia gas. Not only does this cause odors, it also depletes nitrogen that is better kept in the compost for future use by plants.

At any point during composting, you can measure the pH of the mixture. In doing this, keep in mind that your compost is unlikely to be homogeneous. You may have found that the temperature varied from location to location within your compost, and the pH is likely to vary as well. You therefore should plan to take samples from a variety of spots. You can mix these together and do a combined pH test, or test each of the samples individually. In either case, make sure to make several replicate tests and to report all of your answers. (Since pH is measured on a logarithmic scale, it doesn't make sense mathematically to take a simple average of your replicates).

pH can be measured using any of the following methods. Whichever method you choose, make sure to measure the pH as soon as possible after sampling so that continuing chemical changes will not affect your results:

Soil Test Kit

Test kits for analysis of soil pH can be used without modification for compost samples. Simply follow the manufacturer's instructions.

pH Paper

If your compost is moist but not muddy, you can insert a pH indicator strip into the compost, let it sit for a few minutes to soak up water, then read the pH using color comparison.

Compost Extractions

Using a calibrated meter or pH paper, you can measure pH in a compost extract made by mixing compost with distilled water. It is important to be consistent in the ratio of compost to water and to account for the initial moisture content of the compost, but there is no universally accepted protocol specifying these procedures.

One approach is to read the pH in oven-dried samples that have been reconstituted with distilled water.

1. Spread compost in a thin layer in a pan, and dry for 24 hours in a 105-110°C oven.
2. Weigh or measure 5 g samples of oved-dried compost into small containers.
3. Add 25 ml distilled water to each sample.
4. Mix thoroughly for 5 seconds then let stand for 10 minutes.
5. Read the pH with a calibrated meter or with pH paper and record as compost pH in water, or pHw.

An alternative is to measure pH in samples that have not been dried. In this case, the amount of water that you add will need to vary to compensate for the varying moisture content of the compost. You will still need to dry some of the compost in order to measure moisture content, but you can take the pH readings on samples that haven't been altered by drying.

1. Calculate the % moisture of your compost:
   a) Weigh a small container.
   b) Weigh 10 g of compost into the container.
   c) Dry the sample for 24 hours in a 105-110°C oven, or for 5 minutes in a microwave oven. If you use a microwave oven, place a beaker containing 100 ml of water in the oven during the drying to protect the oven's magnetron.
   d) Reweigh the sample, subtract the weight of the container, and determine the moisture content using the following equation:

   $M = ((W_w - W_d)/W_w) \times 100$
   in which:
   M = moisture content (%) of compost sample
   W_W = wet weight of the sample, and
   W_d = weight of the sample after drying.
2. Use the % moisture to figure out how much water to add.
   For example, if your compost sample is 40% moisture, you will compensate by adding only 60% of the water you would need if the sample were air dried (0.60 x 5 ml = 3 ml water needed).
3. Weigh or measure 5 g samples of compost into small containers.
4. Add the calculated amount of distilled water to each sample.
5. Mix thoroughly for 5 seconds.
6. Let stand for 10 minutes.
7. Read the pH with pH paper or a calibrated meter and record as compost pH in water, or pHw.

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Monitoring Compost Odors

A well-constructed compost system should not produce offensive odors, although it will not be odor-free. You can use your nose to detect potential problems as your composting progresses. For example, if you notice an ammonia odor, your mix probably is too rich in nitrogen (the C/N ratio is too low), and you should mix in a carbon source such as leaves or wood shavings. If you smell a musty odor, it may be because the mix is too moist, which you can correct by adding more of your bulking agent. Left uncorrected, compost that is too wet may go anaerobic, producing a foul sulfurous odor that is hard to ignore. If this occurs in indoor bioreactors, you may wish to take them outside or vent them to the outside, then aerate or mix thoroughly and add additional absorbant material such as wood chips or sawdust. In an outdoor compost pile, turning the pile may be sufficent to correct the anaerobic condition, although initially this may make the odor even more pronounced.

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Observing Compost Invertebrates

by Elaina Olynciw

Background

In outdoor compost piles, a wide range of invertebrates take part in the decompostion of organic matter. Try monitoring invertebrate life in the pile over the course of the compost process. How long is it before you locate the first invertebrates? What happens to them when the pile heats up? Do you find different organisms later on, after the pile cools down?

In indoor container composting you may find fewer (or no) invertebrates, and decomposition is accomplished by microbes alone.

Materials

- light-colored trays or pans
- tweezers, spoons, or tongue depressors

Procedure

One method of collecting invertebrates is to take grab samples of compost from various locations in the heap. Some organisms such as centipedes and sowbugs will be more likely to be found near the surface. Others will be found deeper in the heap. Spread each compost sample in a large tray or pan, preferably light in color for maximum contrast. Students should use wooden tongue depressors, plastic spoons, or other instruments that will not hurt the organisms, to sort through the compost. Flashlights and magnifying lenses can be used to enhance the observation. The larger organisms, such as worms, centipedes, millipedes, sowbugs, earwigs, spiders, ants, beetles, snails, slugs, some mites, etc., can be observed with the naked eye. To get a closer look, place samples of the compost in petri dishes or watch glasses and observe them under a dissecting microscope.

An alternative method of separating small arthropods in compost is by using a "Berlese funnel". This method will provide a higher concentration of arthropods to view. Place a funnel with a 10-30 cm upper diameter in a ring stand. Attach a circle of 10mm wire mesh (hardware cloth) or window screen 8 cm below the funnel. Just below the funnel, place a vial to collect the specimens. Position a light source (25 watt) 2.0 - 2.5 cm above the funnel, or place the collecting apparatus in a sunny location. The light and heat drive the negatively phototaxic compost organisms downward through the funnel and into the collecting jar. If you use too strong a light source, the organisms will dry up and die before making it through the funnel.

Place compost in the funnel and then partially fill the vial with water if you want to observe live organisms. Observe the organisms about 2 to 4 days later. They will remain alive and float on top of the water. You can place them in a petri dish or watch glass and observe them under a dissecting microscope or with a magnifying glass. You should find small arthropods, including many different kinds of mites, a few different insect larvae, springtails, small millipedes, ants, etc.

The organisms can be lifted out with a paint brush and maintained in small chambers of plaster of paris (mixed with powdered charcoal to aid observation). This substrate must be kept continually moist to keep the arthropods alive. Adding brewer's yeast to the substrate provides a food supply for many species.

A mixture of 90% percent ethanol and 10% glycerol can be used to collect the arthropods if preserved organisms are needed for quantitative study. A grid of 1.0cm squares can be set up on a petri dish for counting. Removal of organisms can be accomplished with an angled sewing needle that has been filed flat. The pointed end can be imbedded in a cork or wooden dowel or matchstick. Thin, drawn out pipettes can also be used and rinsed out with alcohol if organisms get stuck.

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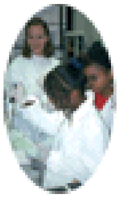

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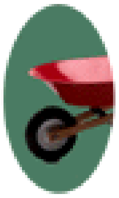

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Observing Compost Microorganisms

Introduction

Observe the microbial communities in your compost over the course of several weeks or months as the compost heats up and then later returns to ambient temperature. Can you identify differences in microbial communities at various stages of the composting process?

Materials

- compound microscope
- .85% NaCl (physiological saline)
- methylene blue stain (Prepare stain by adding 1.6 g methylene blue chloride to 100 ml of 95% ethanol, then mixing 30 ml of this solution with 100 ml of 0.01% aqueous solution of KOH)

Procedure

1. Make a wet mount by putting a drop of water or physiological saline on a microscope slide and transfering a small amount of compost to the drop. Make sure not to add too much compost or you will not have enough light to observe the organisms.
2. Stir the compost into the water or saline (the preparation should be watery) and apply a cover slip.
3. Observe under low and high power. You should be able to find many nematodes (they should be very wiggly), flatworms, rotifers (notice the rotary motion of cilia at the anterior end of the rotifer and the contracting motion of the body), mites, springtails and fast-moving protozoans. Pieces of fungi mycelia can be seen, but might be difficult to recognize. Bacteria can be seen as very tiny, roundish particles, which seem to be vibrating in the background.
4. If you want to observe the bacteria directly, you can prepare a stained slide and observe the slide using a 100X oil immersion lens. To prepare a stained slide, mix a small amount of compost with a drop of physiological saline on a slide. Spread with a toothpick. Let the mixture air dry until you see a white dried film on the slide. Next fix the bacteria to the slide by passing the slide through a

hot flame a few times. Stain the slide using methylene blue stain. Flood the slide with the methylene blue stain for one minute and then rinse with distilled water and gently blot dry using blotting or filter paper.

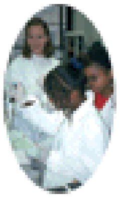
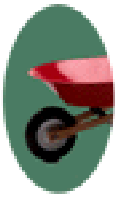
5. Fungi and actinomycetes may be difficult to recognize with the above technique because the entire organism (including the mycelium, reproductive bodies and cells) will probably not remain together. Fungi and actinomycetes will be observed best if you can find fungal growth on the surface of the compost heap. The growth looks fuzzy, powdery, or like a spiderweb. Lift some compost with the sample on top, and and prepare a slide with cover slip to view under the microscope. You should be able to see the fungi well under 100X and 400X. The actinomycetes can be heat-fixed and gram-stained to view under oil immersion at 1000X.
6. To separate nematodes, rotifers, and protozoans, a continuous column of water leading from the compost to the collection vial is necessary, and the following adaptation of the above method should be used: The compost is put into a beaker with the screen stretched across the top and taped in place. The beaker is then turned over into the funnel. Plastic tubing is placed at the end of the funnel stem and a screw clamp is placed a few inches below the end of the funnel stem on the pastic tubing.

   The plastic tubing should lead into a collection vial or small beaker. The clamp is closed and water is poured into the funnel until the beaker is about 1/2 filled. After a few days the clamp is slightly and slowly opened and organisms which have concentrated at the end of the tubing should fall into the vial.

Techniques for Detailed Study of Compost Microorganisms

This protocol was written by Elaina Olynciw, biology teacher at A. Philip Randolph High School, New York City, while working in the laboratory of Dr. Eric Nelson at Cornell University as part of the Teacher Institute of Environmental Sciences.

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Determining Volatile Solids and Moisture Losses

Tom Richard

In large and even medium sized composting systems it can be difficult to directly measure the mass of substrate once the composting process has started, so it is difficult to determine the mass that has been degraded to CO2 and H2O. For a completely mixed reactor, the ash and volatile solids percents of a sample and the original mass data can be used to calculate the volatile solids mass remaining using the following equation:

$$VS_{M^t} = VS_{M^o} \frac{Ash_{\%^o} \times VS_{\%^t}}{Ash_{\%^t} \times VS_{\%^o}}$$

where

VS_{M^t} = the mass of volatile solids at time t

VS_{M^o} = the initial mass of volatile solids

$Ash_{\%^o}$ = the initial percent ash

$VS_{\%^t}$ = the percent volatile solids at time t

$Ash_{\%^t}$ = the percent ash at time t, and

$VS_{\%^o}$ = the initial percent volatile solids

Note that for any sample, ash and volatile solids are related by:

VS%= 100-Ash%

The reduction in volatile solids concentration is gradual and often small, so replicated samples should be ashed to insure a statistically representative result.

You can combine this result with moisture data to determine the moisture loss from the compost. First, calculate the VS loss, and then subtract this DVS from the total dry solids (TS) in the system to get the TS mass at time t (note that the ash fraction of TS is conserved, so the loss of TS is equal to the loss of VS):

$$TS_{M^t} = TS_{M^0} - \left(VS_{M^0} - VS_{M^t} \right)$$

where

TS_{M^t} = the mass of total solids at time t

TS_{M^0} = the initial mass of total solids

VS_{M^t} = the mass of volatile solids at time t

VS_{M^0} = the initial mass of volatile solids

At any point in time, the mass of water remaining in the compost can be calculated from:

$$H_2O_{M^t} = \frac{TS_{M^t} \times H_2O_{\%^t}}{100 - H_2O_{\%^t}}$$

where

$H_2O_{M^t}$ = the mass of H_2O at time t

$H_2O_{\%^t}$ = the percent H_2O at time t

In addition to the mass changes in volatile solids or water, one can also calculate the percent reductions in VS or H2O using the following formulas:

$$(\Delta VS)_{\%} = 100\left[1 - \frac{\left(\dfrac{100 - VS_{\%0}}{VS_{\%0}}\right)}{\left(\dfrac{100 - VS_{\%t}}{VS_{\%t}}\right)}\right]$$

where

$(\Delta VS)_{\%}$ = percent reduction in VS

and

$$\left(\Delta H_2O\right)_{\%} = 100\left[1 - \left(\frac{100 - VS_{\%^0}}{100 - VS_{\%^t}}\right) \times \left(\frac{H_2O_{\%^t}}{H_2O_{\%^0}}\right) \times \left(\frac{100 - H_2O_{\%^0}}{100 - H_2O_{\%^t}}\right)\right]$$

where

$\left(\Delta H_2O\right)_{\%}$ = percent reduction in H_2O at time t

Acknowledgement:

Many thanks to Mr. Vladimir Knezevic for correcting an error in the formula for the percent reduction in the mass of water. The corrected formula was posted on this page November 17, 2000.

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Oxygen Transport

Tom Richard

Convection and diffusion are the two mechanisms by which oxygen moves from the open air into a composting matrix and ultimately to the microorganisms themselves. Oxygen transport is intimately related to the moisture content of the compost, as both convection and diffusion are reduced by water saturated pores. Capillary theory and matric potential relationships provide a theoretical framework for evaluating the effects of moisture content on air filled porosity.

Convection

Convection can be categorized as either "forced" (driven by mechanical means) or "natural" (caused by the bouyancy of hot air). In a system with mechanical aeration, blowers move air through the larger pores at relatively high velocities. In a passive system, hot air can often be seen slowly rising out of the tops of piles, and natural convection pulls cool oxygen rich air in to replace it.

Water filled pores create a major impediment to uniform convective air movement, by creating zones of high resistance. As air short-circuits through unsaturated zones, the aerobic regions generate more heat and become even drier, while the wetter regions become anaerobic. One of the principal functions of mixing and turning compost is to redistribute moisture, to minimize this preferential airflow and the nonuniform decomposition that results.

Diffusion

While these convective mechanisms are important for the pile overall, oxygen diffusion through the smaller pores and into the aqueous film surrounding compost particles is essential to maintaining aerobic conditions for the active microorganisms. A saturated matrix also dramatically reduces oxygen diffusion, which is 6000 to 10,000 times greater in air than in water. Diffusion can be mathematically modeled for the range of conditions in a composting matrix, as described in the pages below:

Oxygen Diffusion

- Calculating the oxygen diffusion coefficient in air
- Calculating the oxygen diffusion coefficient in water

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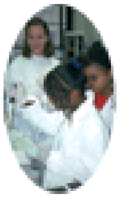

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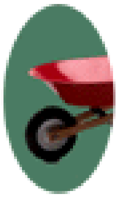

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For general questions about composting, please browse this and other composting websites, or make use of the compost listserves.

For specific comments related to this page, please contact the Cornell Waste Management Institute (format and style), or Tom Richard (technical content).

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Oxygen Diffusion

Tom Richard

Diffusion is a reflection of the fact that molecules, as they vibrate with random motion in a gas or liquid, move toward an equilibrium where all the molecular species in the mixture are uniformly dispersed, and the concentration of any one species is the same everywhere.

The diffusion equation (Fick's second law), states that the rate of molecular diffusion is proportional to the second derivative of its concentration. It its most general form this can be written:

$$\frac{\partial c_A}{\partial t} = D_{AB} \nabla^2 c_A \qquad (1)$$

where c_A = the concentration of molecular species A [mole/cm^3]

t = time [sec]

D_{AB} = diffusion coefficient for the binary pair AB [cm^2/sec], and

The Laplacian operator ∇^2 is defined in rectangular coordinates as:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

where x, y and z = distances [cm] in the coordinate system

Source: Bird et al., 1960.

For a one dimensional concentration gradient of oxygen in air, this simplifies to:

$$\frac{\partial c_{O_2}}{\partial t} = D_{O_2-Air} \frac{\partial^2 c_{O_2}}{\partial^2 x} \qquad (2)$$

where

c_{O_2} = the concentration of oxygen [mole/cm^3]

D_{O_2-Air} = diffusion coefficient [cm^2/sec]

For a one dimensional concentration gradient of oxygen in water, the simplified equation is:

$$\frac{\partial c_{O_2}}{\partial t} = D_{O_2-H_2O} \frac{\partial^2 c_{O_2}}{\partial^2 x} \qquad (3)$$

where c_{O_2} = the concentration of oxygen [mole/cm^3]

$D_{O_2-H_2O}$ = diffusion coefficient [cm^2/sec], and

In a composting system, the concentration gradient is a function of the rates of oxygen supply and aerobic ***biodegradation and oxygen uptake*** (link coming soon). The O2 concentration gradient is the driving force that moves O2 into the pile by diffusion, and there is a corresponding CO2 gradient driving diffusion of CO2 out of the pile. From the practical standpoint of process management, it is the diffusion of O2 that is critical to maintaining aerobic conditions, so that will be the focus of the present analysis.

A detailed discussion is provided for calculating the oxygen diffusion coefficient in air, as well as the procedure for calculating the oxygen diffusion coefficient in water. Using this analysis, we find that the O2 diffusion coefficient in saturated air (at 15% O2 concentration) is 5700 to 10,800 times greater than in water (at 60°C and 20°e;C respectively). When oxygen is forced to diffuse through water saturated pores, this restriction on oxygen transport is one of the most important factors leading to anaerobic conditions.

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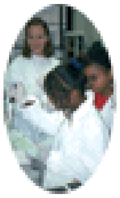
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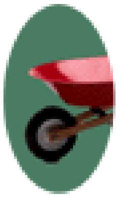
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Calculating the Oxygen Diffusion Coefficient in Air

Tom Richard

This discussion is part of a section on oxygen transport and oxygen diffusion in compost, which provides background on the general concepts and equations.

Diffusion theory for gases is based on the kinetic molecular theory of gases, initially developed by Ludwig Boltzman and James C. Maxwell in the 19th century. This theory provides a rigorous set of equations which allow us to calculation diffusion coefficients under a wide range of conditions.

The Effects of Temperature and Pressure on Diffusion

The diffusion coefficient D is a function of both temperature and pressure. Diffusion increases with increasing temperature (as molecules move more rapidly), and decreases with increasing pressure (which packs more molecules in a given volume, making it harder for them to move). These temperature and pressure effects are illustrated by equation (1),which applies to the diffusion coefficient between any two components of a mixture (called a binary pair):

$$D_{AB_{T_j,P_j}} = D_{AB_{T_i,P_i}} \left(\frac{P_i}{P_j}\right)\left(\frac{T_j}{T_i}\right)^{\frac{3}{2}} \frac{\Omega_{D/T_i}}{\Omega_{D/T_j}} \qquad \textbf{(1)}$$

where

D_{AB} = diffusion coefficient for the binary pair at

P = pressure

$\Omega_{D/T}$ = collision integral for molecular diffusion, which is a function of kT/ε_{AB}

where k = Boltzman constant = 1.38×10^{16} ergs/°K and

ε_{AB} = energy of molecular interaction [ergs]

and i and j are reference and modeled conditions respectively

Source: Bird et al., 1960[1]; Welty et al., 1984[2]

For binary pairs of oxygen with nitrogen, carbon dioxide, and water, and in the temperature range from 0°C to 80°C, $\kappa T/\varepsilon_{AB}$ ranges from about 1.3 to 3.5. Using tabulated values for κ/ε_A for each of the gases in the mixture (see Table 1), κ/ε_{AB} was calculated for each binary pair according the square root rule:

$$\varepsilon_{AB}/\kappa = \sqrt{\varepsilon_A/\kappa} + \sqrt{\varepsilon_B/\kappa} \qquad (2)$$

Source: Welty et al., 1984

The collision integral Ω can be approximated from tables relating it to $\kappa T/\varepsilon_{AB}$. For the $\kappa T/\varepsilon_{AB}$ values of interest Ω ranges from about 1.3 to 0.9 (decreasing as $\kappa T/\varepsilon_{AB}$ increases). For this series of calculations a 5th order polynomial was fit to the $\kappa T/\varepsilon_{AB}$ - Ω data tabulated in appendix K1 of Welty et al. (1984).

For each binary pair of interest, equation (1) can then be used to calculate the binary diffusion coefficients as functions of temperature and pressure, given a diffusion coefficient measured at a known temperature and pressure. Table 1 provides the diffusion coefficients at atmospheric pressure and two temperatures for the most important constituents in an aerobic composting environment.

Table 1.

Oxygen Diffusion Coefficients of Binary Gas Pairs at Atmospheric Pressure

Binary Pair	**Temp [°C]**	ε_A/κ **[°K]**	**Diffusion Coefficient [cm2/s]**
Oxygen - Carbon Dioxide	20 60	146	0.153 0.193
Oxygen - Water Vapor	20 60	201	0.240 0.339
Oxygen - Nitrogen	20 60	102	0.219 0.274

Mixtures of Gases

While air has relatively uniform constituency (with the exception of water vapor), the composition of gases in a compost pile varies, particularly with respect to O_2 and CO_2, for the reasons described above. In order to accurately calculate the O_2 diffusion coefficient under these various conditions, we need to consider the relative proportions of all the gases in the mixture.

The diffusion coefficient for a mixture can be calculated from:

$$D_{1-mixture} = \frac{1}{y_2'/D_{1-2} + y_3'/D_{1-3} + \ldots + y_n'/D_{1-n}} \qquad (3)$$

where the subscripts 1 – n denote each binary pair and

y_n' = mole fraction of component n in the gas mixture, evaluated on a component – 1 – free basis

$$y_n' = \frac{y_n}{y_2 + y_3 + \dots + y_n}$$

Source: Wilke (1950)[3]; as cited in Welty et al., 1984

Substituting the values from Table 1 in equation (3), we can calculate the diffusion constant for oxygen in a mixture of these gases, given the mole fraction of each. The results of this calculation are provided in Table 2, for variations of O_2, relative humidity, and temperature. For each calculation, increases in the O_2 mole fraction are assumed to be offset by CO_2 increases in the calculation.

Table 2.

Effect of Temperature and Gas Mixture on Oxygen Diffusion Coefficients

		Oxygen Diffusion Coefficient [cm^2/s]	
Temperature	**Relative Humidity**	**at 2% O_2**	**at 15% O_2**
20°C	50%	0.203	0.214
20°C	100%	0.203	0.214
60°C	50%	0.259	0.273
60°C	100%	0.264	0.278

From the results in Table 2 it is clear that temperature has a much greater impact on the oxygen diffusion coefficient than the gas mixture composition, with O_2 concentration of secondary importance and relative humidity having little effect. It is important to remember that the oxygen concentration enters the diffusion equation in two ways, both embedded in the diffusion coefficient (as described above), and as the driving force through its concentration gradient. As the driving force, oxygen concentrations do have a very significant effect on the magnitude of diffusive oxygen transport.

We can also estimate the oxygen diffusion coefficient in water under conditions typical of composting systems A comparison between the diffusion coefficients in these two phases illustrates why adequate air filled porosity is essential for aerobic composting.

Acknowledgment:

Jean VanderGheynst provided helpful comments and suggestions during the preparation of this document.

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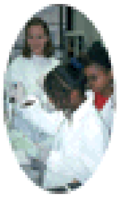

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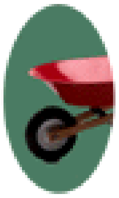

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Calculating the Oxygen Diffusion Coefficient in Water

Tom Richard

This discussion is part of a section on oxygen transport and oxygen diffusion in compost, which provides background on the general concepts and equations.

Estimates of the diffusion coefficient in liquids often use a correlation developed by Wilke and Chang, 1955, which is based on the Stokes-Einstein equation:

$$D_{O_2-H_2O} = 7.4 \times 10^{-8} \frac{T\left(\psi_{H_2O}\ M_{H_2O}\right)^{\frac{1}{2}}}{\mu\ V_{O_2}^{0.6}}$$

where

T = Absolute temperature [°K]

ψ_{H_2O} = an "association" parameter for the solvent water = 2.26 (Reid et al., 1977)

M_{H_2O} = molecular weight of water = 18 g/mole

μ = viscosity of water, in centipoises (see table 1)

V_{O_2} = the molar volume of oxygen = 25.6 cm^3/g - mole (Welty et al., 1984)

This equation, which lacks the rigorous theoretical foundation used to develop the equations for gas mixtures, is usually accurate to ± 10% for dilute solutions of nondissociating solutes (Bird, et al., 1960).

For the purposes of this analysis, we neglect the effects of dissolved substrate and microorganisms and assume that the solvent is water. Substituting the given values into this equation, we can calculate the diffusion constant for oxygen in an aqueous solution. The results of this calculation, for the range of temperatures common in composting systems, are provided in table 1.

Table 2.

Effect of Temperature and on the Oxygen Diffusion Coefficients in Water

Temperature	**Viscosity of H_2O [centipoises] (Weast, 1969)**	**O_2 Diffusion Coefficient [cm2/s]**
20°C	1.002	0.0000197
40°C	0.653	0.0000324
50°C	0.547	0.0000399
60°C	0.467	0.0000482

From these results we can see that the oxygen diffusion coefficient in water is strongly affected by temperature. This effect is even stronger than was the case in air, more than doubling as temperatures increase from 20°C to 60°C.

The other, more significant, comparison with the oxygen diffusion coefficient calculated in air is the magnitude of the coefficient. The O2 diffusion coefficient in saturated air (15% oxygen) is 5,700 to 10,800 times greater than in water (60°C and 20°C respectively). When oxygen is forced to diffuse through water saturated pores, this restriction on oxygen transport quickly leads to anaerobic conditions.

These implications are discussed in further in the section on factors leading to anaerobic conditions.

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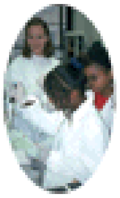
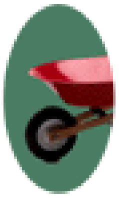


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Capillary Theory and Matric Potential

Tom Richard

Moisture content affects oxygen transport in several ways. The first effect of moisture content on oxygen diffusion is the increase in aqueous film thickness around individual particles in the mixture. The second effect, and the topic of this discussion, is a matrix effect, acting on the aggregate of compost particles. As moisture content increases, capillary action fills the small pores with water, often dramatically increasing the distance oxygen must diffuse through the aqueous phase. The theory that predicts these capillary effects is based on soil matric potential (Ψ_m) rather than moisture content, but these two parameters are related. Miller (1989) fit a linear relationship to data from a mixture of sewage sludge and wood chips:

$$M = 64.049 + 0.142\,\Psi_m \qquad (1)$$

where

M = moisture content (percent)

Ψ_m = matric water potential (kPa) (usually expressed as a negative number)

In this mixture the matric potential was zero at 64% moisture, but both this intercept and the slope may vary for different materials and mixtures. Miller (1996) also indicated that a second order polynomial (Figure 2, 1989) fit the data somewhat better than the linear relationship given. Serra-Wittling et al. (1996), working with muncipal solid waste compost, measured a matric potential of -10 kPa at 62% moisture, agreeing with Miller's result at least at high moisture contents.

If we view the compost matrix as an idealized mixture of solids and pores which take the form of capillary tubes, equilibrium between the upward forces of surface tension and the downward force of gravity will be found at:

$$h = \frac{2\sigma\cos\alpha}{\rho g r} \qquad (2)$$

where

h = height of rise of fluid in the capillary tube (m)

σ = surface tension of fluid against air

(for water, σ= 0.073 kg/s^2 at 20°C and 0.067 kg/s^2 at 55°C)

α = contact angle of water with the tube (radians), (for water, $\cos\alpha \cong 1$)

ρ = density (for water, ρ= 998 kg/m^3 at 20°C and 986 kg/m^3 at 55°C)

g = acceleration due to gravity ($g = 9.81\ m/s^2$)

r = equivalent radius of tube (m)

(Bear, 1972; Weast, 1969; Kabat and Beekma, 1994)

If we assume the fluid in the pores has the same properties as water, the matrix is a bundle of uniform tubes, and neglect other forces such as osmotic potential, we can set $h\rho g = -\Psi_m\ (\mathrm{Pa})$ and solve for the radius at any given matric potential. The result, for the properties of water at 55°C, is:

$$r = \frac{0.000135}{-\Psi_m} \quad \text{where } \Psi_m \text{ is measured in kPa and } r \text{ in meters} \qquad (3)$$

The assumptions stated above make it clear that this result is greatly simplified version of reality. Nonetheless, it illustrates the dramatic effect increases in moisture have on the size of air filled pores near saturation. Combining equation (3) with Miller's (1989) relationship between moisture content and matric potential, Table 1 gives the critical air filled pore radius at a given moisture content. Pores larger than this critical dimension remain largely air filled, while smaller pores are filled with water.

Table 1. Critical Pore Radius

Moisture Content (%)	**Matric Potential (kPa)**	**Critical pore radius (mm)**
30	-239.8	0.00056
40	-169.4	0.00080
50	-98.9	0.00136
55	-63.7	0.00212
60	-28.5	0.00473
62	-14.4	0.00935
64	-0.3	0.391
64.048	-0.00007	19.2

As moisture content increases from 60 to 64%, the critical radius increases from 0.005 mm to 0.4 mm, and an additional small increase from 64 to 64.05% will saturate all pores for this particular mixture. It is important to reiterate that this example is based on Miller's (1989) relationship described in equation 1, above, and other mixtures will saturate at different moisture contents, varying between 60% to over 70% in some cases. For a compost mixture with its largest particles in the recommended range of 1.3 to 7.6 cm (Gray et al, 1971), it is easy to see that small increases in moisture content in the range near saturation will quickly fill most of the pores with water, with a corresponding reduction in the potential for diffusion to supply needed oxygen to the decomposition process.

Acknowledgement:

Marc Jalbert provided helpful comments and corrected an error in the previous version of this document (corrected Nov. 8, 2000).

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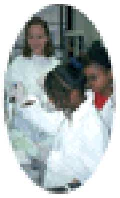

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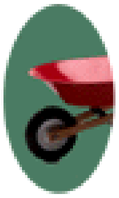

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Odor Management

Tom Richard

Odor is perhaps the most common problem associated with composting, and the failure to adequately address it has led to numerous neighbor complaints and the closure of many large scale facilities. Fortunately, for the most part odors can be controlled, but proper management can take time and money.

At many composting sites odors originate with the incoming ingredients, which may have been stored anaerobically (without oxygen) for a week or more before transport to the site. Once these ingredients are incorporated into the composting system, subsequent odor problems are usually a result of low oxygen or anaerobic conditions. ***Anaerobic odors - (coming soon!)*** include a wide range of compounds, most notoriously the reduced sulfur compounds (e.g. hydrogen sulfide, dimethyl sulfide, dimethyl disulfide, and methanethiol), volatile fatty acids, aromatic compounds and amines. Ammonia is the most common odor that can be formed aerobically as well as anaerobically, and thus has its own set of managment options.

Incoming ingredients

If organic feedstocks are already anaerobic and odorous when they arrive at the site, they need to be brought to an aerobic state as quickly as possible. Usually this means combining them with a coarse, dry bulking amendment to increase the porosity and allow oxygen penetration. Experiences vary as to the optimum frequency of subsequent turning, which depends on how thoroughly materials are mixed initially, as well as the porosity of the pile. If the porosity is adequate, it may make sense for the material to sit for a few days or weeks to get through the initial period of high oxygen demand.

Oxygen

Oxygen is the obvious compound to add when the source of the odors is anaerobic metabolism. Forced aeration systems provide a way to mechanically introduce oxygen, and are common at facilities composting materials like biosolids (sewage sludge) with a high potential to generate odors. These systems require relatively uniform pile shapes and porosity to reduce the potential for air to short-circuit along the path of least resistance. In passively aerated systems, which depend on diffusion and natural convection, adequate porosity is essential to reduce the resistance to oxygen movement. The pile or windrow dimensions must also be appropriate for both the mix of ingredients and stage in the composting process, so that the oxygen diffusing into the pile is not entirely consumed before it reaches the center.

In addition to these traditional approaches to aeration, oxidizing chemicals like hydrogen peroxide, potassium permanganate, and chlorine are used by the wastewater treatment industry for odor control. These compounds will chemically oxidize anaerobic odors, but may kill the composting microorganisms as well. This is especially true for chlorine. In low concentrations, evenly incorporated in a pile, a compound like potassium permanganate could be effective, but would probably also be expensive.

Odors can also be biologically oxidized after they have formed, and this is probably tremendously important for most composting systems. Odorous anaerobic products produced in the low oxygen center of a pile usually pass through an aerobic zone on the way out. Microorganisms will then degrade the odors aerobically. This process probably occurs on both a macro scale (the pile as a whole) and a micro scale (within individual particles or clumps), essentially providing *in situ* biofiltration. When turning an anaerobic compost pile this advantage is lost, which is why frequent turning is not the best way to deal with an odor problem, and instead often makes the problem worse. In a windrow system, it is far better to address the fundamentals of porosity and pile size to insure adequate passive aeration (diffusion and convection) throughout the compost pile.

Catalysts and Innocula

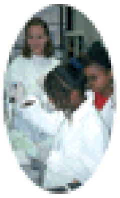
Catalysts purport to degrade odorous compounds, usually via biologically generated enzymes. A catalyst facilitates a reaction without itself being permanently changed by the reaction, and thus each enzyme can act on many molecules of an odorous compound before it is eventually degraded. Enzymatic catalysts are normally applied either on the surface of a compost pile or in the airspace above it. A number of products are on the market, but very little independent research has been done to verify their effectiveness.

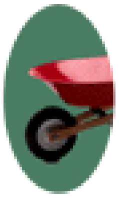
Summary

Preventing excessive odors requires consistent management of the composting process, starting with prompt attention to incoming ingredients. Wet materials should be mixed with a porous bulking amendment to provide the necessary pre-conditions for oxygen transport, and then must be aerated or turned as required during the active stages of the composting process. Understanding the factors leading to anaerobic conditions, including the interactions of particle size, porosity, moisture, and oxygen transport, will provide additional insights into odor prevention. While the emphasis should always be on prevention, ***odor treatment - (coming soon!)*** may also be required, particularly in sensitive neighborhoods.

Acknowledgments

Helpful reviews and discussions related to this document were provided by James Gossett, Nancy Trautmann, Daniel Cogan, and Cary Oshins.





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Ammonia Odors

Tom Richard

Ammonia is among the most common odors found at composting facilities. Fortunately, ammonia is not a pervasive odor, so it does not require a large number of dilutions to reduce concentrations below the odor threshold. Ammonia also disperses easily, since is lighter than air (its density is 60% that of air), and does not settle in low lying areas the way hydrogen sulfide and other dense odorous compounds do. These factors make ammonia odors more prevalent on-site than off-site.

Ammonia odors can be formed aerobically as well as anaerobically, so the control strategies recommended for anaerobic odors may not apply. Noticeable ammonia losses primarily result from a low C/N ratio. The microorganisms are very efficient at utilizing nitrogen when that is the limiting nutrient. The smell of ammonia is an indicator that nitrogen is in excess, and carbon/energy is limiting instead. Ammonia losses are common when composting high nitrogen materials such as fresh grass clippings or manure, and are often accompanied by other nitrogen losses in runoff or infiltration. At large composting facilities these nitrogen losses could threaten surface or groundwater quality.

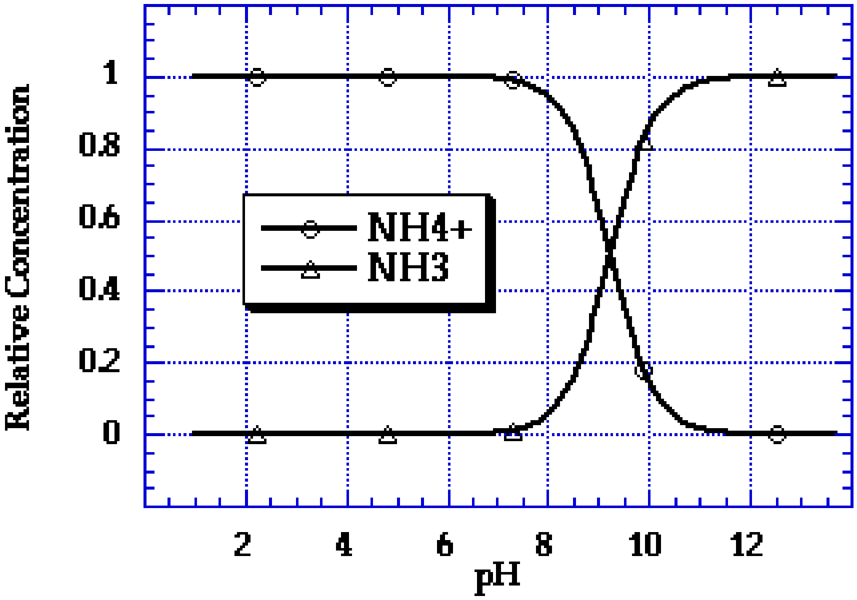
Another factor affecting the magnitude of ammonia volatilization is pH. NH_3 (gaseous ammonia) and NH_4^+ (aqueous ammonium ion) are in equilibrium at a pH of about 9, with higher pH's forcing more NH_4^+ into the gas form that you can smell. Thus ammonia is rarely noticed if the pH is acidic , and adding lime to a pile will increase the ammonia odor. The equilibrium relationship is defined by the following equation.

$$NH_4^+ \longleftrightarrow NH_3 + H^+$$

$$\frac{\left[NH_3\right]\left[H^+\right]}{\left[NH_4^+\right]} = 5.7 \times 10^{-10}$$

Source: Sawyer and McCarty, 1978)

A plot of this equation, showing the relative concentrations of NH_3 and NH_4^+, is provided below.



In a real composting system this equilibrium relationship would have to be corrected somewhat if there are other ions in solution, or if the compost is at a temperature other than 25°C.

Zeolites (natural ion exchange resins/minerals) can be used to trap excess nitrogen, and are being tried on a pilot basis at a few composting facilities. In this case it is the ammonium ion form that is bound. Assuming pH doesn't change, lowering the NH_4^+ concentration will also reduce the NH_3 concentration proportionately, as the two forms adjust to a new equilibrium. The zeolite that is most effective at trapping ammonium ions in wastewater applications is clinoptilolite. Composters should be sure to avoid the common water softener Sodium Zeolite, as the sodium will be released into the compost rendering it too salty for use (Burkhardt, 1995). Interestingly, in wastewater applications the zeolite is usually regenerated using lime - $Ca(OH)_2$ - in which calcium (Ca^{++}) replaces the ammonium ions (NH_4^+) and converts them to gaseous ammonia (NH_3), which is then discharged to the atmosphere. Obviously we don't want this regeneration process to occur in a composting pile, so be careful of this approach with high lime materials.

Acknowledgments

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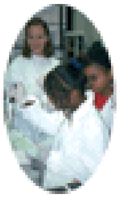
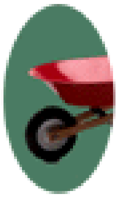


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Factors Leading to Anaerobic Conditions

Tom Richard

Significant release of anaerobic odors from a composting system is usually a symptom that some important management factor has been neglected or misunderstood. This discussion is an attempt to enhance your understanding of the conditions which can lead to odor formation, in the hopes that they can be avoided or at least minimized in the future.

The most common factors which result in anaerobic odors are:

1) excess moisture,
2) inadequate porosity,
3) a rapidly degrading substrate, and
4) excessive pile size.

All of these factors make it more difficult for oxygen to penetrate throughout a pile before it is depleted, or allow airflow to short-circuit around large zones which become anaerobic. One of the mechanisms of oxygen transport is diffusion, which is function of the concentration difference between the outside air (21% oxygen) and the oxygen concentration in the interior of the pile (if anaerobic, zero). In a passively aerated or windrow system, diffusion is assisted by natural convection, but that assistance is probably limited to the upper and outer parts of the pile (Miller et al., 1989). Even with a forced aeration system, the blower's effects are mostly confined to large pores, and diffusion is needed to drive oxygen movement from the large pores into small pores and the aqueous films surrounding particles.

If we examine the equations governing oxygen diffusion in air, we see that diffusivity increases with temperature, and decreases with increasing pressure. Under conditions typical of composting systems, the gas phase oxygen diffusion coefficient can range from 0.20 cm^2/sec to 0.28 cm^2/sec .

While the diffusion coefficient can vary depending on the conditions in the gas phase, even more dramatic effects are seen when the oxygen has to diffuse through water rather than air. In water at 60°C, the oxygen diffusion coefficient is approximately 4.8 x 10^{-5} cm^2/sec, almost 4 orders of magnitude smaller than that in air. Because the impact of moisture is so dramatic, excess moisture is the most common factor leading to anaerobic conditions.

Reference

Miller, F.C., E.R. Harper, and B.J. Macauley. 1989. Field examination of temperature and oxygen relationships in mushroom composting stacks - consideration of stack oxygenation based on utilization and supply. Australian Journal of Experimental Agriculture 29(5):741-750. Return to citation in text.


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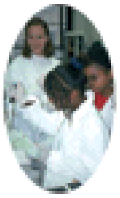
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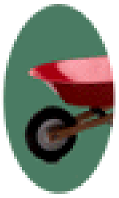
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Excess Moisture

Tom Richard

Because oxygen diffuses so much slower in water than in air, excess moisture reduces oxygen penetration. This reduction occurs in two ways. First, because moist compost is hydrophilic (it loves water), water is strongly held to the surfaces of particles, so as water content increases the thickness of the aqueous film surrounding each particle increases. The second, closely related effect, is a matrix effect due to capillarity -- water fills the smallest pores first, and thus creates water filled zones between particles, which slow oxygen diffusion and result in anaerobic clumps.

Moisture and aqueous film thickness

Figure 1 is an illustration of the first effect, aqueous film thickness, at the scale of an individual particle.

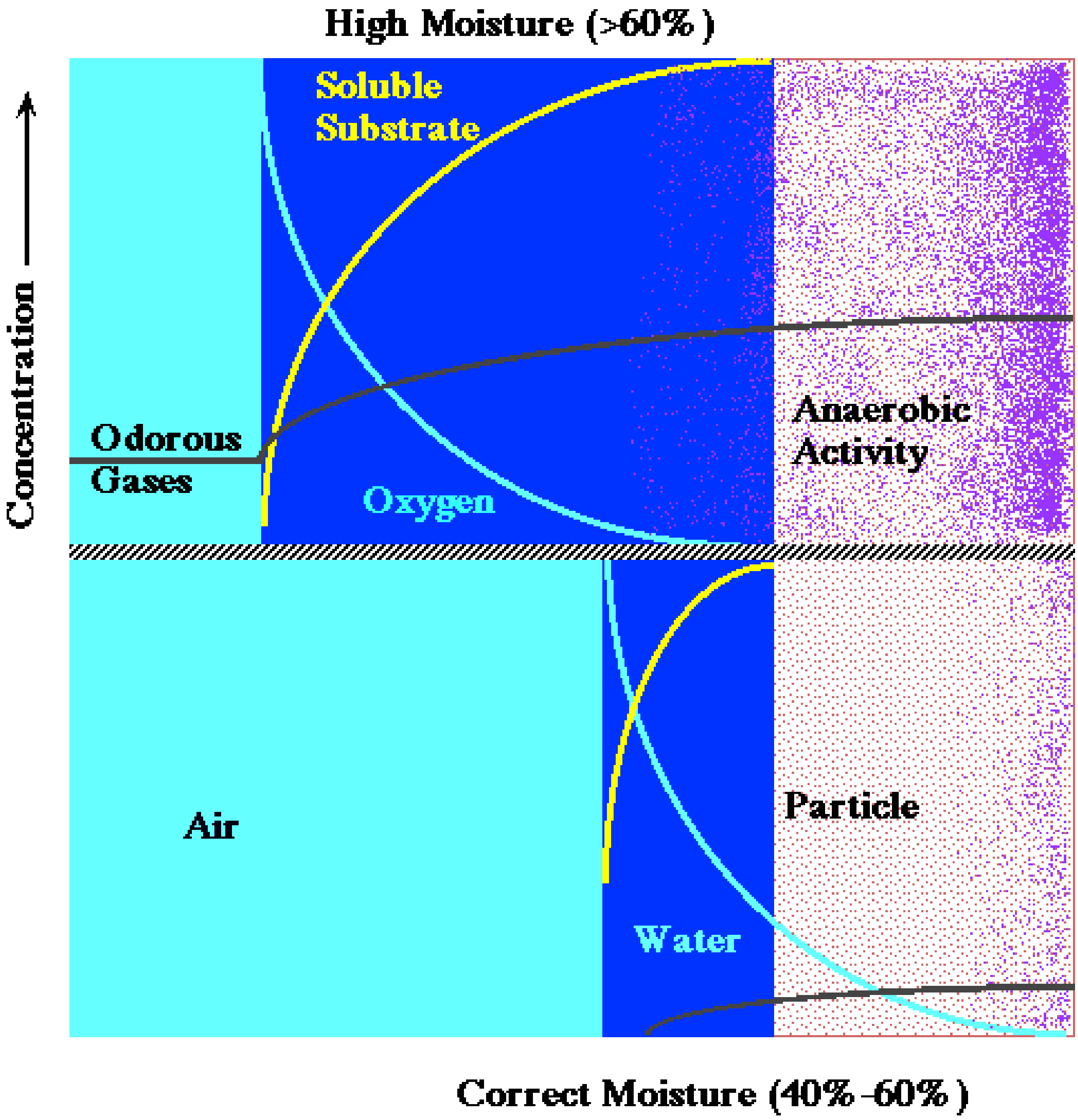

Figure 1. The effect of aqueous film thickness on anaerobic odor production.

The top half of the figure illustrates a particle with a thick film of water, while in the lower half of the figure the film thickness is considerably reduced. Note that in both cases the substrate concentration is high at the particle surface, the oxygen concentration is high at the air/water interface, and the oxygen concentration decreases as it moves into the film and substrate is oxidized. In the interior of the particle, where the oxygen concentration approaches zero, anaerobic metabolic activity (indicated by purple dots) produces odors, some of which are oxidized as they diffuse out toward the airstream. With a thick layer of water (which typically occurs with moisture contents greater than 60%), oxygen is depleted before it can fully penetrate the aqueous film, and the levels of odorous gases generated in the anaerobic zone is so high that even after some oxidation in the outer layers of the aqueous film, they are detectable in the airstream. When the aqueous film is thinner (moisture contents between 35 and 60%), oxygen penetrates further, odor concentrations in the liquid are lower, and they are oxidized before they can diffuse back out into the airstream.

Figure 2 illustrates the effects of moisture content on the location of aerobic, fermentation, and anaerobic zones within a particle and in the aqueous film surrounding it. Regions of primarily aerobic metabolism are indicated with yellow dots, the fermentation zone is indicated with pink dots, and anaerobic metabolic regions are indicated with purple dots. Although many of the most offensive odors are anaerobically generated, fermentation can generate alcohols and other "sweet" or "silage" type smells which some people may find offensive. If these fermentation odors are prevalent they indicate large areas of the composting system are anoxic (without oxygen), and any further restrictions on oxygen transport may lead to anaerobic odor problems. Alcohols and other fermentation products, like the anaerobic odors, will degrade aerobically if given sufficient opportunity.

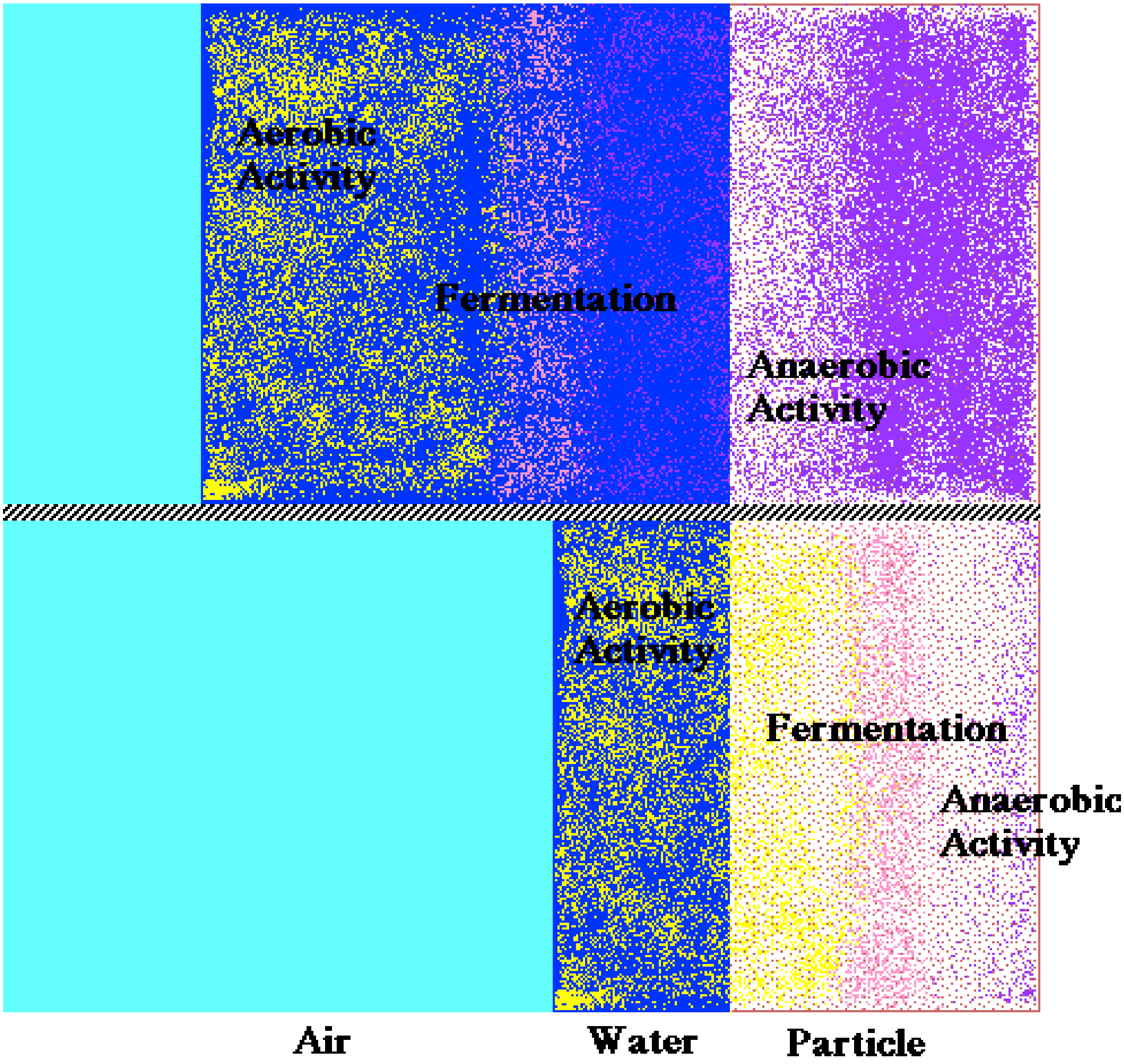

Figure 2. Metabolic Regions as a function of moisture content.

The second limitation of increasing moisture content on oxygen diffusion is through the filling of small pores with water, often dramatically increasing the distance oxygen must diffuse through the aqueous phase. The effective size of pores filled at different moisture contents can be analyzed on the basis capillary theory and matric potential relationships, applying approaches developed for soil physics and porous media.

The resulting anaerobic zones within an otherwise aerobic matrix are illustrated by the contrast between figures 3 and 4. In figure 3, the compost is at an appropriate moisture content, with aqueous films surrounding particles and air filled pores between particles. The arrows indicate a hypothetical depth that oxygen can penetrate from an air filled pore, which in this case completely penetrates all the particles.

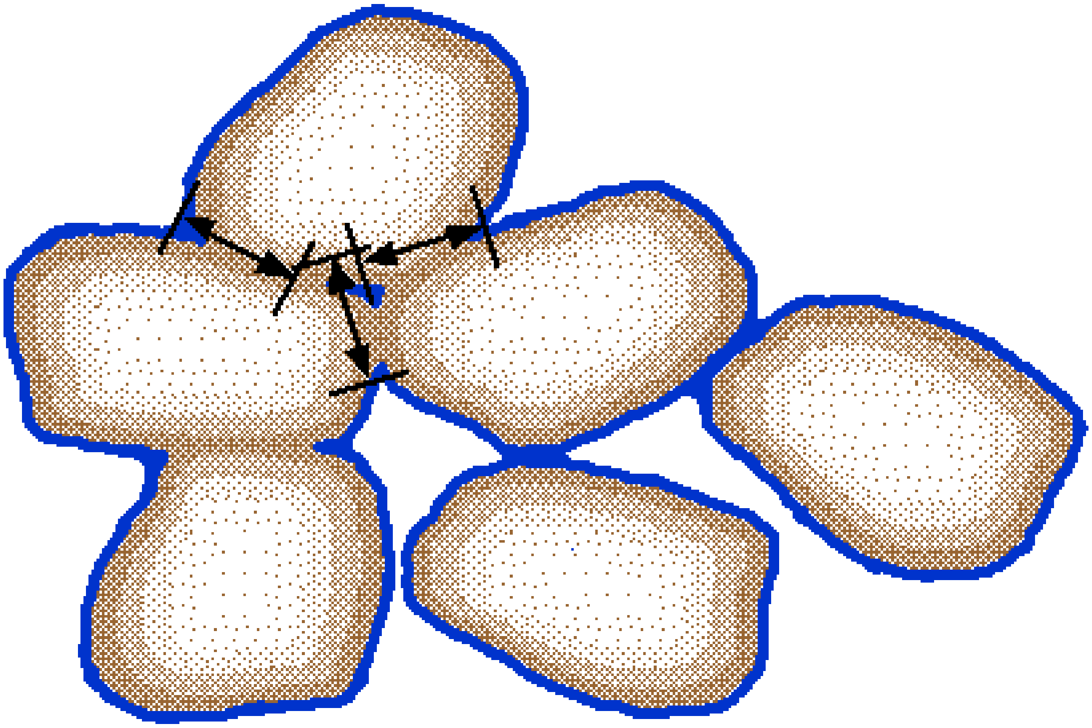

Figure 3. In a properly moist compost matrix, the particles (brown) are surrounded by aqueous films (blue), but are separated by air filled pores (white).

Figure 4 illustrates those same particles with a higher moisture content. Note that all but the largest pores have filled with water, leading to considerable regions of anaerobic activity

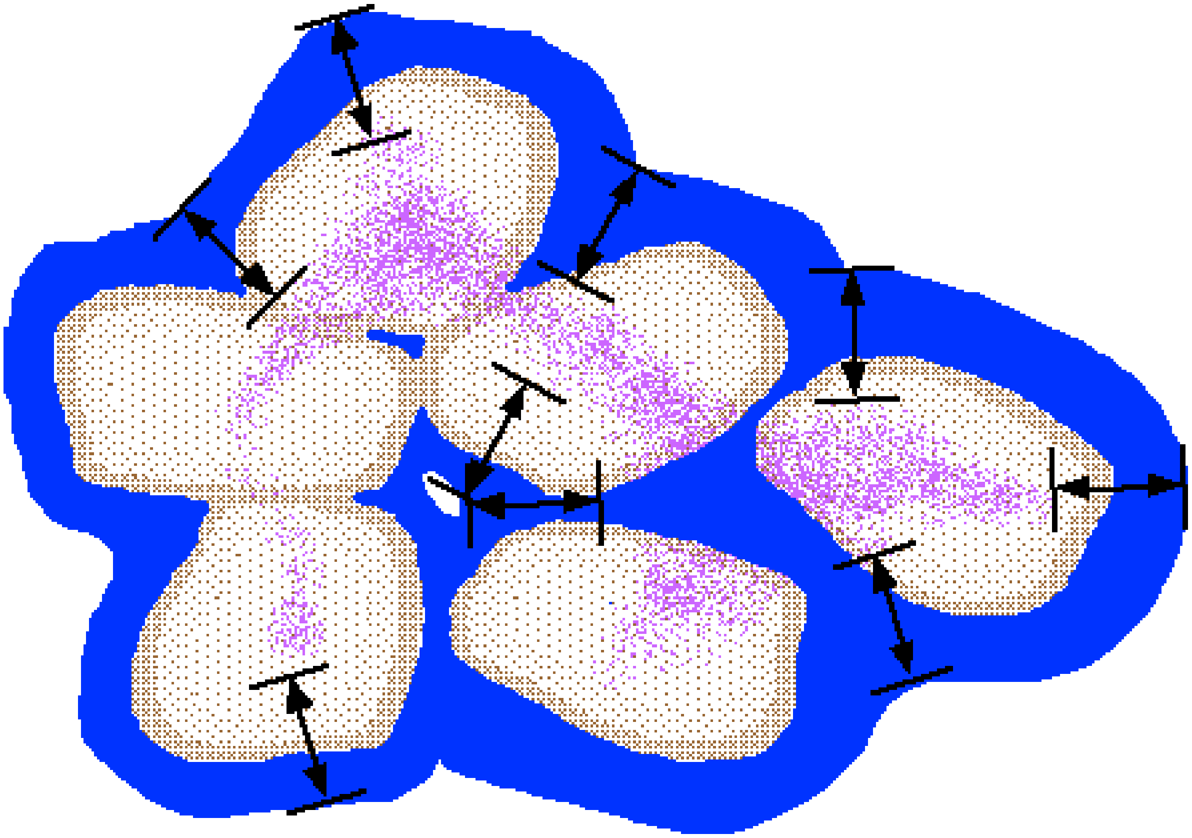

Figure 4. Anaerobic zones (purple dots) are created as increasing water content fills small pores, so oxygen must diffuse farther through water.

With most composting materials, as moisture content increases beyond about 60%, the pores will rapidly fill and anaerobic conditions will result. But even at normally acceptable moisture content, anaerobic conditions are likely if compaction or small particle sizes lead to inadequate porosity.


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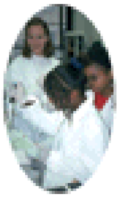
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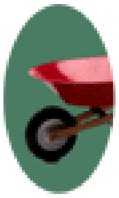
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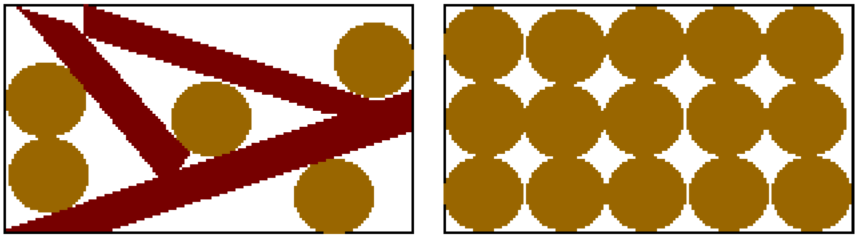
Inadequate Porosity

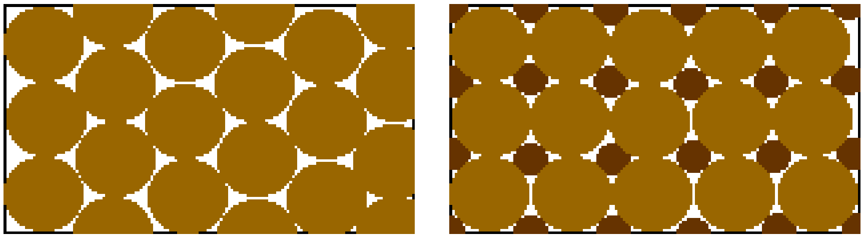
Tom Richard

The particle size distribution, bulk density, and porosity of a compost mixture are the second group of factors that can lead to anaerobic conditions. These physical characteristics of the compost mixture can interact with high moisture levels to reduce oxygen transport. Small particle sizes reduce the number of large pores and increase the likelihood that oxygen will need to diffuse a long way through small pores (which are more likely to be filled with water, as described in the section on capillary theory and matric potential).

The shape, size, and structure of particles affects how they settle, with tight packing arrangements increasing the bulk density and reducing the air filled porosity (free air space). Compaction (caused mechanically or by the weight by overburden in tall piles) encourages tight packing as well. Several of these effects are illustrated in Figure 1 below:


loosely packed,
well structured material

loosely packed,
uniform particle size


tightly packed,
uniform particle size

tightly packed,
mixed particle sizes

Figure 1. Effective cross sectional area as a function of particle size distribution, shape, and packing density.

The white space between the particles in figure 1 illustrates the effective cross sectional area of each matrix. Estimates of effective cross sectional area can be used to apply the diffusion equation to a porous media like compost, correcting for the fact that diffusion only occurs in the pore space and is further constrained by tortuosity of those pores. A useful result of this correction is the apparent diffusion coefficient, which in soils has been shown to be roughly proportional to the square of the air filled porosity (Papendick and Campbell, 1981):

$D_{\text{effective}} = S^2 \times D$

where

$D_{\text{effective}}$ = effective diffusion coefficient

S = air filled porosity, and

D = the diffusion coefficient in air

Assuming a compost matrix experiences similar effects, we can use this equation to estimate the impact of density on diffusion. Since any increase in bulk density is at the expense of the air filled porosity (the solid and aqueous phases can be considered incompressible), relatively small changes in volume can have a significant effect.

For example, suppose a pile of compost has an initial air filled porosity of 30%, and the volume of a pile is reduced by 10% through compaction and size reduction after the first pass of a windrow turner. Assuming constant moisture and solids content, the air filled porosity would be reduced from 30% to 20%, a 33% reduction [(0.30-0.20)/0.30], and the apparent diffusion coefficient will be reduced by 56% [(0.09 - 0.04)/0.09]. This significant change in oxygen diffusion might easily pass unnoticed in the windrow itself, where volume reductions of greater than 50% are common, and 80% is not unheard of with an initially loose material like autumn leaves.

To the extent that natural or forced convection is important in oxygen transport, small diameter pores can cause problems even if total air filled porosity is maintained. The increased frictional resistance from the walls in small pores reduces any mass flow of oxygen that would otherwise occur. In addition, the air channels in a composting matrix are not a bundle of continuous straight tubes, but twist and bend in tortuous path, with many dead ends and narrow passages. These factors further reduce oxygen transport in ways that are difficult to quantify.

The physical characteristics of the compost matrix affect the ease with which oxygen can move into a pile. But the distance it penetrates is also a function of how quickly it is being used up. A rapidly degrading substrate, like grass clippings or food scraps, can use up oxygen more rapidly than it is being replaced.

Reference

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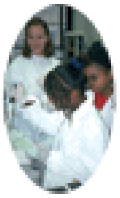

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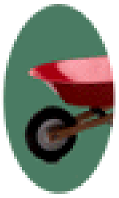

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Rapidly Degrading Substrate

Tom Richard

The oxygen content at any location in a composting pile reflects a balance between oxygen supply and oxygen consumption. Rapidly degrading substrates like grass clippings or food scraps consume oxygen much more rapidly than leaves or digested sewage sludge. Oxygen consumption is a function of substrate characteristics (C/N ratio, bioavailability, moisture, particle size, and other issues -- described in the section Getting the Right Mix) and environmental conditions (temperature, moisture, oxygen concentration, and pH -- described under chemistry and physics in the background information section).

Oxygen uptake rates measured in compost vary widely, from less than 1 to over 10 g O2/kg volatile solids per hour (Haug, 1993). Rates for a variety of substrate materials under typical environmental conditions are detailed in the section on biodegradation rates and oxygen uptake (coming soon) .

To provide for the increased oxygen demand of a rapidly degrading substrate, oxygen supply must also be increased. In forced aeration systems this can often be accomplished by increasing the blower size or operating frequency. With passive systems, any restrictions on oxygen transport such as inadequate porosity or excess moisture must be reduced. A final alternative, which is commonly practiced with grass clippings and food scraps, is to reduce the pile size.

Reference

Haug, R.T. 1993. The Practical Handbook of Compost Engineering. Lewis Publishers, Boca Raton. 717 pp. Return to citation in text.

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Excessive Pile Size

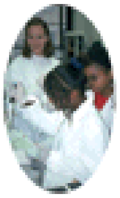
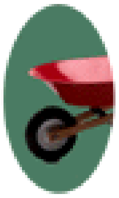
Tom Richard

Composting comes in many shapes and sizes, from 1 liter vacuum bottles to warehouse sized industrial systems. In all of these systems, the correct pile size balances the heat generated by microbial decomposition with the heat lost through conduction, convection, and radiation, keeping most of the compost between 40°C and 60°C (for more on the mechanisms of heat loss, see the physics page in our background information section).

Passively aerated systems, which depend on diffusion and natural convection for oxygen transport, usually have a large open surface area to encourage air movement, with corresponding convective heat losses. This large surface area also results in conductive and radiant heat loss. Because heat loss in these systems is largely a function of exposed surface area (as well as ambient temperatures), and microbial heat generation largely a function of volume (assuming the environmental conditions are near optimum), for any material and configuration there will be an ideal surface to volume ratio. Larger piles, with a smaller surface to volume ratio, will tend to overheat, while small piles will be too cool. For materials in a typical windrow configuration (where the width of the windrow is about double the height), the ideal height will usually be in the range of 1 to 3 meters. Rapidly degrading, dense mixtures that include grass clippings, food scraps or manure will be at the lower end of this range, while porous, slowly degrading piles of leaves will be at the upper end.

With a forced aeration system, convective heat loss can be increased by increasing the aeration rate. Although this will reduce the average temperature of the pile, one also has to be careful to insure that the temperature extremes are not too great. With very large piles, regions near the air inlet will be excessively cooled and dried, while other regions near the exhaust may be to hot. As with passively aerated systems, the ideal size of a forced aeration pile depends on the characteristics of the material being composted and the geometry of the composting system. For most materials, in systems using ambient air (air once through), the maximum height (or airflow path length) is 2 to 3 meters. Tunnel reactor systems, which can recycle the airflow, typically operate at higher airflow rates with a smaller temperature difference between the inlet and the outlet. Recycling the airflow, or using pre-heated air, thus allows an increase in reactor size while still maintaining a tolerable degree of process control.

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Odor Treatment - Biofiltration

Tom Richard

Odor control is one of the primary concerns of large scale composting facilities, especially those located near residential areas. While good process management and careful housekeeping can greatly reduce odors, in many cases some method of odor treatment will still be required. There are several options for odor treatment, including chemical stripping, thermal destruction, and biofiltration. In many cases biofiltration is both the least expensive and most effective treatment option, which has led to its widespread use in the composting industry today.

Biofiltration

A biofilter uses moist organic materials to adsorb and then biologically degrade odorous compounds. Cooled and humidified compost process air is typically injected through a grid of perforated pipes into a bed of filtration media. The materials that have been used for biofilter construction include compost, soil, peat, chipped brush and bark, sometimes blended with a biologically inert material such as gravel to maintain adequate porosity. Biofilter bed depths typically range from 1 to 1.5 meters deep, with shallower beds subject to short-circuiting of gas flow and deeper beds more difficult to keep uniformly moist. Biofilters have been shown to be effective at treating essentially all of the odors associated with composting, including ammonia and a wide range of volatile organic compounds (including sulfur compounds and amines).

The principle design criteria is the airflow rate per unit surface area of the biofilter. Literature values for biofilter airflows range from 0.005 to 0.0025 m/s (1 to 5 cfm/ft^2) and are typically 0.015 to 0.02 m/s (3 to 4 cfm/ft^2). For the purpose of selecting the biofilter blower, the backpressure expected across the biofilter at this airflow rate is usually in the range of 20 to 120 mm H2O/m depth (0.22 to 0.9 inches H2O/ft), although the pressure drop can be considerably higher through dense composts and soil.

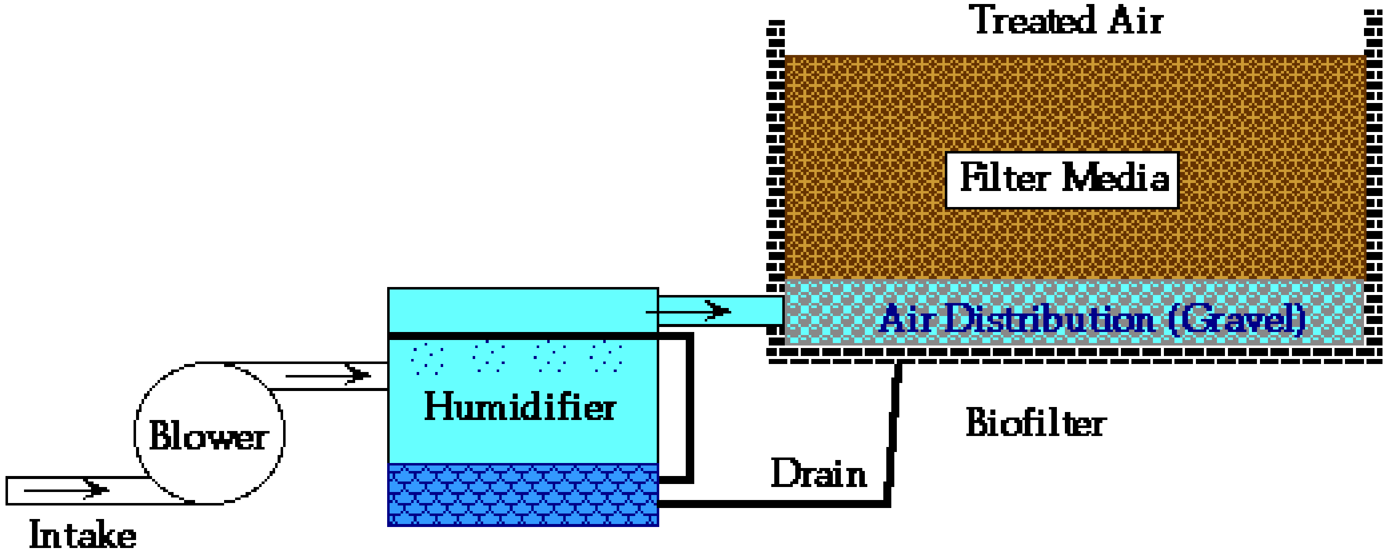
For soil filters, standard specifications are (in SI units, from Skoda, 1991):

- linear velocity of gas: 0.5-1 cm/s
- static pressure of gas: < 250 mm Hg
- humidity of gas: non-saturated with water
- temperature of gas: 5-40°C

- moisture content of soil: 40-70% of maximum water holding capacity
- temperature of soil: optimum between 20-37°C
- pH of soil: optimum about 7

Unsaturated air coming out of the compost building will dry the biofilter and rewetting from the surface is generally not uniform. A simple humidification scheme is illustrated in the schematic diagram below.

Biofilter Schematic:



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Williams, T.O. and F.C. Miller. 1992. Biofilters and facility operations. BioCycle 33(11):75-79.

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Water Quality Protection

Tom Richard

Composting has long been viewed as an environmentally beneficial activity. To maintain that positive reputation it is essential that compost facilities consider and mitigate any adverse environmental impacts. Water quality protection can be accomplished at most composting facilities by proper attention to siting, ingredient mixtures, and compost pile management.

The results of water quality monitoring studies at Cornell and elsewhere indicate that outdoor windrow composting can be practiced in an environmentally sound manner (Richard and Chadsey, 1994; Rymshaw et al., 1992; Cole, 1994). However, there are a few aspects of this process that can potentially create problems. For leaf composting, the primary concerns are BOD and phenol concentrations found in water runoff and percolation. Biochemical Oxygen Demand and phenols are both natural products of decomposition, but the concentrated levels generated by large-scale composting should not be discharged into surface water supplies. Additional potential concerns when composting nutrient rich materials such as grass, manure, or sewage sludge include nitrogen compounds such as nitrate and ammonia, and in some cases phosphorus as well. With manure or sewage sludge there may also be pathogen concerns. These concerns, while important, are readily managed, and can be mitigated through careful facility design and operation.

A water quality threat?

Facility Design

Selecting the right site is critical to many aspects of a composting operation, from materials transport and road access to neighborhood relations. From an environmental management perspective, the critical issues are soil type, slope, and the nature of the buffer between the site and surface or groundwater resources. Soils can impact site design in a variety of ways. If the soils are impermeable, groundwater is protected from nitrate pollution, but runoff is maximized which increases the BOD, phosphorus, and pathogen threat to surface water. On the other hand, highly permeable soils reduce the runoff potential but may allow excessive nitrate infiltration to groundwater. Intermediate soil types may be best for sites which are operated on the native soil. For some large facilities, or those handling challenging waste materials, a working surface of gravel, compacted sand, oiled stone or even asphalt or concrete may be appropriate. Such surfaces can improve trafficability during wet seasons considerably, but the surface or groundwater quality issues remain.

The buffer between the site and surface or groundwater resources is the first line of defense against water pollution. Deep soils, well above the seasonally high water table, can filter solid particles and minimize nitrate migration. Two feet of such vertical buffer are required by New York State regulations, and while a greater depth would be advantageous, such soils are rare in many parts of the state. Horizontal buffers are required to be a minimum of 200 feet from wells or surface water bodies and 25 feet from drainage swales in New York State. Although the nature of this horizontal buffer is not specified in the regulations, grass can help filter the runoff and minimize pollutant migration. Such vegetative filter strips are further described below.

Site design issues which may impact on water quality include the selection of a working surface (native soil or an improved surface), exclusion of run-on to the site by surface diversions, possible drainage of wet sites, and the possible provision of roofs over some or all of the composting area to divert precipitation and keep compost or waste materials dry. In all but fully roofed sites there will be surface runoff which may need to be managed as described below. Slope of the site a surface drainage to either divert uphill water away from the site or collect site runoff for management should be considered in the design process.

A number of factors combine to determine the quality of water running off compost sites. One obvious factor which is often overlooked is the excess water running onto the site from upslope. Diversion ditches and berms which divert that water around the site will minimize the runoff which needs to be managed. Siting the facility on a soil with moderate to high permeability will also significantly reduce the runoff generated on the site. For the runoff which remains, alternatives to surface discharge include such simple technologies as soil treatment, filter strips, or recirculation, so that sophisticated collection and treatment systems should not be needed.

These simple, low-cost treatment strategies have proven effective for a variety of wastewaters and organic wastes (Loehr et. al., 1979). Soil treatment forces the percolation of water through the soil profile, where these organic compounds can be adsorbed and degraded. Vegetative filter strips slow the motion of runoff water so that many particles can settle out of the water, while others are physically filtered and adsorbed onto plants. Recirculation would involve pumping the runoff water back into the compost windrows, where the organic compounds could further degrade and the water would be evaporated through the composting process. This last option should work very well during dry summer or early fall weather, when water often needs to be added, but would not be appropriate if the moisture content of the compost was already high.

Operations

The day to day operation of the composting site offers considerable opportunities to minimize water quality impacts. The proper selection, mixing, and management of materials can help control overall runoff, BOD, pathogen and nutrient movement. Assuring appropriate moisture and carbon to nitrogen (C:N) ratios throughout the composting process can be very effective at limiting these pollutants. A review of the basic principles of compost facility operations, with more detailed discussion of these issues as well as data on C:N ratios, water content, and bulk density of some common agricultural composting materials are provided in the NRAES On Farm Composting Handbook (Rynk et al., 1992) and the Getting the Right Mix section of these web pages.

Nitrate is most easily controlled by maintaining an appropriate C:N ratio in the composting mixture. Raw materials should normally be blended to approximately 30:1 carbon to nitrogen ratio by weight. The ratio between these key elements is based on microbial biomass and energy requirements. Inadequate nitrogen (a high C:N ratio) results in limited microbial biomass and slow decomposition, while excess nitrogen (a low C:N ratio) is likely to leave the composting system as either ammonia (odors) or nitrate (water pollution). In a nitrogen limited system microorganisms efficiently assimilate nitrate, ammonia and other nitrogen compounds from the aqueous phase of the compost, thus limiting the pollution threat.

The ideal ratio of carbon to nitrogen will depend on the availability of these elements to microbial decomposition. Carbon availability is particularly variable, depending on the surface area or particles and the extent of lignification of the material. Composting occurs in aqueous films on the surfaces of particles, so greater surface area increases the availability of carbon compounds. Lignin, because of its complex structure and variety of chemical bonds, is resistant to decay. For both of these reasons the carbon in large wood chips is less available than that in straw or paper, so greater quantities of wood chips would be required to balance a high nitrogen source like manure.

The data from experimental studies indicates low C:N ratio mixtures can generate nitrate levels above the groundwater standard (Rymshaw et al.; 1992, Cole, 1994) Much of this nitrate in runoff and leachate will infiltrate into the ground. While microbial assimilation and denitrification may somewhat reduce these levels as water passes through the soil, these processes will have a limited effect and are difficult to control. Proper management of the C:N ratio is perhaps the only practical way to limit nitrate contamination site short of installing an impermeable pad and water treatment system.

The other important factor to consider when creating a composting mixture is water content. From a microbial standpoint, optimal water content should be in the 40 to 60% range. This moisture content is a balance between water and air filled pore space, allowing adequate moisture for decomposition as well as airflow for oxygen supply. The ideal water content will vary somewhat with particle size and density, and fine, dense organic substrates should be drier if adequate aeration is to be assured. Excess water, in addition to increasing the odor potential via anaerobic decomposition, will increase the runoff and leachate potential of a composting pile during rainfall events.

With both C:N ratios and moisture content, the optimum water and nitrogen levels for rapid composting may create a greater than necessary water pollution threat. Increasing the C:N ratio from 30:1 to 40:1 and decreasing the water content from 60 % to 50% may slow down decomposition somewhat, but can provide an extra margin of safety in protecting water quality.

Once the materials are mixed and formed into a compost pile windrow management becomes an important factor. Windrows should be oriented parallel to the slope, so that precipitation landing between the windrows can move freely off the composting area. Pile shape can have a considerable influence on the amount of precipitation retained in a pile, with a flat or concave top retaining water and a convex or peaked shape shedding water, particularly in periods of heavy rain. These effects are most pronounced when the composting process is just starting or after a period of dry weather. In the early phases of composting a peaked windrow shape can act like a thatched roof or haystack, effectively shedding water. Part of this effect is due to the large initial particle size, and part is due to waxes and oils on the surfaces of particles. Both of these initial effects will diminish over time as the material decomposes. During dry weather the outer surface of even stabilized organic material can become somewhat hydrophobic, limiting absorption and encouraging runoff.

If a pile does get too moist, the only practical way to dry it is to increase the turning frequency. The clouds of moisture evident during turning release significant amounts of water, and the increased porosity which results from turning will increase diffusion and convective losses of moisture between turnings. This approach can be helpful during mild or warm weather, but caution must be exercised in winter when excessive turning can cool the pile.

Runoff management

Implementation of the preventative measures described above can considerably reduce the water pollution threat. However, some facilities may require additional management of runoff from the site. As indicated above, the runoff pollutants of primary concern are BOD and phosphorus, largely associated with suspended solids particles. Pathogenic cysts may either be absorbed on particles or be free in solution, and again the relative significance is not adequately researched. Four readily available strategies exist to help control these pollutants: vegetative filter strips, sediment traps or basins, treatment ponds, and recirculation systems.

This simplest runoff management strategy is the installation of a vegetative filter strip. Vegetative filter strips trap particles in dense surface vegetation. Grasses are commonly used, and must be planted in a carefully graded surface over which runoff can be directed in a thin even layer. Suspended particles flowing slowly through the grass attach to plants and settle to the soil surface, leading to a significant reduction in BOD levels.

Sediment traps operate by settling dense particles out of the runoff. Particles settle by gravity during passage through a basin of slowly moving water. This approach can be particularly effective for removing phosphorous associated with sediment. Because much of the BOD and nitrogen in compost site runoff will be in light organic particles, the effectiveness of this approach may be somewhat limited. However, it will help limit sediment movement off the site, and can be a useful adjunct to either a vegetative filter strip or a treatment pond, enhancing the effectiveness of each.

During dry periods of the year compost runoff can be recirculated to the compost piles themselves, or alternately used to irrigate cropland or pasture. The nutrients as well as moisture can thus serve a useful purpose, either by supplying needed moisture to the compost windrows or by providing nutrients and water to crops. However, a recirculation system requires both a pumping and distribution system and adequate storage capacity for prolonged wet periods. While this approach offers a closed system which appears ideal for pathogen control, care may need to be taken to separate runoff from the fresh manure to avoid contaminating finished compost or crops.

Storage requires the construction of a pond, which can also be used to treat the waste. Ponds can be designed for aerobic or facultative treatment of runoff water. In either case microorganisms continue the decomposition process started in the compost pile, but in an aqueous system. As the organic material stabilizes, the BOD levels will drop. Pathogen levels are also expected to drop, although the rate will be dependant on seasonal temperature variations and will be slow during winter in unfrozen portions of a pond. To be effective, ponds must be designed to contain the runoff from major storm events, with an adequate residence time for microbial stabilization. Details of pond design vary with climate, runoff characteristics, and pond effluent requirements. The Natural Resources Conservation Service (NRCS) has considerable expertise in adapting treatment systems to the local situation.

Runoff collection pond

All these treatment options will help with nitrogen and phosphorus removal as well as BOD and pathogens. Sediment basins and ponds will settle out particulate matter, which includes bound nutrients such as phosphorus. However, these sedimentation mechanisms are not likely to remove nutrients or BOD as well as soil adsorption and crop uptake in a land treatment system. For nitrogen removal, vegetative filter strips and irrigation systems can both be effective, and either is enhanced by alternating flow pulses with rest periods. Phosphorus removal is most efficient under aerobic conditions, and irrigation systems generally show higher removal rates than vegetative filter strips although either can be effective. Although little is currently known about the effectiveness of these approaches in destroying the pathogens of concern, increased opportunities for adsorption, desiccation, and other forms of environmental and microbiological stress are integral to the physical and biological treatment processes described. An appropriate combination of these removal mechanisms can be designed to address the pollution parameters of local concern.

Summary

Water quality protection at a composting site can be accomplished through proper site design, operations, and runoff management. Composting facilities vary widely in size, materials processed, and site characteristics, and all these factors will effect the design of appropriate preventative measures. Although the available evidence is limited, current indications are that runoff from composting windrows has BOD and nutrient levels comparable to low strength municipal wastewaters. Land treatment systems which have proven effective for these alternative wastewaters we can expect to be effective for windrow composting facilities as well.

References

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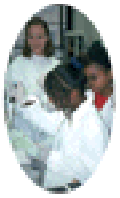
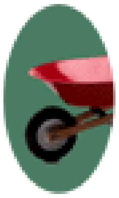
Rynk, R., M. van de Kamp, G.B. Willson, M.E. Singley, T.L. Richard, J.J. Kolega, F.R. Gouin, L. Laliberty, Jr., K. Day, D.W. Murphy, H.A.J. Hoitink, and W.F. Brinton. 1992. On-Farm Composting Handbook. NRAES, Cornell University, Ithaca, NY. 186 pp.

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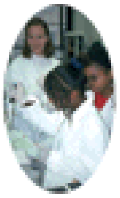
Science & Engineering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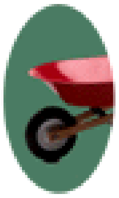
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Welcome to . . .
CORNELL Composting

This website provides access to a variety of composting educational materials and programs developed at Cornell University.

Everything you ever wanted to know about composting, but were afraid to ask?

Not quite, but we do hope we've assembled some useful information.

The Cornell Composting Website was developed by Tom Richard, Nancy Trautmann, Marianne Krasny, Sue Fredenburg and Chris Stuart.

New! Compost Marketing & Labeling Project

Compost Survey Maps and Database

Search our maps and database for compost facilities throughout New York State. See the results of a survey that was recently conducted by the Cornell Waste Management Institute to locate composting facilities throughout the State of New York.

Compost Case Studies

The Cornell Waste Management Institute project to increase the capacity to compost the tremendous amount of food scraps produced in New York State. Includes decriptions of sponsored projects including Cornell's own Food Scrap Composting operation.

Science and Engineering

This section outlines the basic science and engineering principles involved in the composting process. There are a number of calculations and experiments you can try out on your own.

Composting in Schools

A special section for students and teachers using composing in the classroom. Don't miss the section on "weird and unusual composting."

Composting Resources

An annotated listing of written and audio visual publications, with prices and ordering information. Many slides and illustrations are also provided, so if you have a slow connection you may want to turn off automatic image loading.

Composting Contacts

Please direct all general inquiries to one of the resources on this list.

For general questions about composting, please browse this and other composting websites, or make use of the compost listserves.

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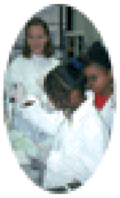
Composting in Schools

- Why Composting?
- Teacher's Page
- Ideas for Student Research Projects
- Compost Quiz
- Science and Engineering
- Composting Indoors
- Composting Outdoors
- Weird and Unusual Composting
- Frequently Asked Questions
- Glossary

The information in this site, and a whole lot more, is contained in our book **Composting in the Classroom** and video **It's Gotten Rotten**.


Cornell Composting


Science & Engineering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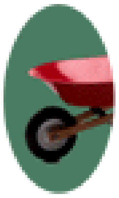
Resources


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Credits

Awards

Back to the **Cornell Composting Homepage**

Additional resources from the Cornell Waste Management Institute

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The resources listed below are available from the following address unless otherwise noted:

Cornell University Resource Center
7 Business & Technology Park
Ithaca, NY 14850
Phone: 607-255-2090
Fax: 607-255-9946
E-mail: resctr@cornell.edu
CornellCooperative Extension On-Line Catalog

WRITTEN

Composting Challenges and Solutions in New York State

A Summary of the series of Rountables conducted in Upstate NY in the summer of **1998**.

Reducing the NYC Waste Stream: The Potential Role for Composting

A Summary of the April 3, **1998** Composting Roundtable.

Master Composter Program Implementation Guide & Master Composter Resource Manual by CWMI - 1998

A sourcebook for Master Composters and Educators. For more info see the description on the Educational Resource Page

Composting in the Classroom: Scientific Inquiry for High School Students, by Nancy Trautmann and Marianne Krasny - 1997

A comprehensive guide for teachers interested in guiding composting research projects by high school students. ISBN 0-7872-4433-3. Available from Kendall/Hunt Publishing Co., 1-800-228-0810 (US) or 1-319-589-1000 (International).

Agricultural Composting: A Feasibility Study for New York Farms - 1993

Supported by the NYS Dept. of Agriculture & Markets, this study explores equipment and labor costs, land and management requirements. Out of Print - available in electronic form only (145 K).

MSW Composting Fact Sheet Series - 1993

7 fact sheets developed from a special issue of Biomass & Bioenergy, 4-6 pgs. each. Produced by the Cornell Waste Management Institute. Purchase from Cornell University Resource Center, $7.

On-Farm Composting Handbook - 1992

Comprehensive, up-to-date guide on many aspects of farm-scale composting. Produced by and available from the Northeast Regional Agricultural Engineering Service (NRAES), Cornell University, 152 Riley-Robb Hall, Ithaca, NY 14853; 607-255-7654; 186 pgs., $25.

Municipal Yard Waste Composting: Operator's Fact Sheets - 1992

10 fact sheets covering the different aspects of operating a composting facility. Produced by Department of Agricultural & Biological Engineering at Cornell University. Available from Cornell University Resource Center, $4.

Composting at Home, Let It Rot!! It's Nature's Way of Recycling

Composting handbook available free from Cornell Cooperative Extension of Albany County, Martin Rd, PO Box 479, Voorheesville, NY 12186; phone: 518-765-3500.

Composting to Reduce the Waste Stream: A Guide to Small Scale Food and Yard Waste Composting-1991

Explains how to construct and maintain a compost pile. Outlines factors that affect the composting process including aeration, moisture and temperature. Illustrations, tables, diagrams, and step-by-step instructions for constructing compost bins. Produced by and available from the Northeast Regional Agricultural Engineering Service, Cornell University, 152 Riley-Robb Hall, Ithaca, NY 14853; 607-255-7654, $7.

Composting: Waste to Resources

A 36 page guide on the how-to's of composting for the beginner, including youth and educators, also two posters and designs for compost systems. Available from Cornell Resource Center, $8.

Economics of Yard Waste Composting in Westchester County, NY

Report shows that home, municipal and regional composting of yard waste can reduce the net economic and environmental costs of solid waste management in Westchester County. Available from Dept of Ag Econ, Publications, Warren Hall, Ithaca, NY 14853; 607-255-2102.

Fact Sheet and Viewpoint 2: "Yard Waste Composting," and "Composting as a Waste Management Strategy New Directions-New Questions"

Produced by the Cornell University Waste Management Institute. 4 pgs. each, available from Cornell University Resource Center, $3/set.

Home Composting Brochure - 1989 (Catalog code 329FFHSW)

Produced by the Cornell Department of Agricultural Engineering. Available from Cornell University Resource Center, $1.

Municipal Compost Management Home Study Program - 1991

An approach to assessing, designing, and managing a composting system for municipalities. The Municipal Compost Management video program contains all of the materials needed to conduct an effective workshop. Developed by the Cornell University Waste Management Institute, with funding from ShopRite supermarkets. Available from the Home Study Program, Warren Hall, Cornell University, Ithaca, NY 14853; 607-255-2226, $95. The complete educational video program is $295.

Yard Waste Management: A Planning Guide for NYS - 1990

Outlines the major considerations of municiple yard waste management, and provides the information needed to design an effective program. Prepared by Agricultural & Biological Engineering, Cornell University. Available from NYSDEC, 50 Wolf Rd, Albany, NY 12233; 518-457-7337.

Yard Waste Management in New York State: Case Studies and the Economics of Composting - 1996

Community and Environmental Management Series No. 1, Cornell Local Government Program, March 1996. (147 pgs). Presents a comprehensive overview of the status of municipal yard waste management activities in NYS as of the early 1990s. Existing municipal sites are categorized according to idealized mixed waste, low, medium or high intensity management scenarios. Survey data summarizing the cost, revenue, collection, end-product use and operational characteristics of existing facilities are reported by scenario. Detailed descriptions and cost/revenue budget worksheets for seven municipal facilities are included. Available from the Cornell Local Government Program, 214 Warren Hall, Cornell University, Ithaca, NY 14853; 607-255-1583, $5.

Energy and Municipal Yard Waste Management - 1996

Community and Environmental Management Series No. 2, Cornell Local Government Program, March 1996. (88 pgs). Estimates and compares the amounts of energy typically utilized or generated in collecting, transporting, managing and otherwise disposing of yard wastes. Comparisons are based on scenarios typical of NY municipalities. The energy implications of a variety of collection, composting, chipping, methane recovery and waste-to-energy technologies are considered. Available from the Cornell Local Government Program, 214 Warren Hall, Cornell University, Ithaca, NY 14853; 607-255-1583, $5.

AUDIO VISUAL

COMPOST: Truth or Consequences

Truth or Consequences is our new video, designed for people who would like to take the mystery out of home composting. The information is presented in an informal, entertaining way to make learning about composting fun!

It's Gotten Rotten

A 20-minute video designed to introduce high school students to the science of composting. It focuses primarily on the biology of the invertebrates and microorganisms that decompose organic matter. Available from Cornell University Resource Center.

Home Composting

48 slides/script on backyard composting, developed by Cornell Cooperative Extension. Available on loan to NYS Cooperative Extension agents from the Home Grounds Lending Library, 20 Plant Science Bldg., Cornell University, Ithaca, NY 14853; 607-255-3134.

Yard Waste Composting for Municipalities - 1989

Slide set produced by the Cornell Agricultural and Biological Engineering Department, $49/loan $18. Available from Cornell University Resource Center.

Composting Exhibit - 1988

Produced by Cornell Cooperative Extension. Three-panel display and accompanying fact sheet on composting. True/false questions wired to light up, when correctly answered. Available on loan to NYS Cooperative Extension agents only, for $20/day or $40/week from the Cornell University Resource Center.

Recycling Yard Waste, A Tour of Community Programs - 1991

35-minute video showing different municipalities recycling yard waste through composting and chipping as an alternative to traditional waste disposal techniques. Produced to help local officials and citizens make informed choices about managing municipal yard waste. Available from Cornell University Resource Center, $48/loan $18.

Turning Over an Old Leaf: The 20% Solution - 1992

7-minute video produced to help citizens and local officials understand how composting and chipping yard wastes can save them money. Available from Cornell University Resource Center, $24/loan $18.

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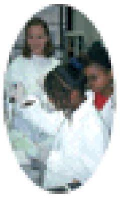
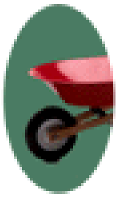
Science & Engineering



Composting in Schools



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Organizations:

Natural Resource, Agriculture, and Engineering Service (NRAES)

(formerly Northeast Regional Agricultural Engineering Service)

http://nraes.org

NRAES produces and distributes many up-to-date comprehensiveguides related to composting. You may find "On-Farm CompostingHandbook" NRAES-54, or "Field Guide to On-Farm Composting",NRAES-114 and/or "Composting for Municipalities, Planningand Design Considerations" NRAES-94 useful. They are availablefrom Natural Resources Agricultural Engineering Service (NRAES).See their contact information below. A complete list of NRAESpublications is also available. E-mail orders are accepted.

*Please note that NRAES distributes and markets publicationsbut does not have experts on staff to answer questions about composting.

Cooperative Extension
152 Riley-Robb Hall
Ithaca, NY 14853-5701
Phone: 607-255-7654
Fax: 607-254-8770

e-mail: nraes@cornell.edu

To place an order:

http://nraes.org/nraesform.html

On-Farm Composting page:

http://nraes.org/publications/nraes54.html

General publications page:

http://nraes.org/publications.html

The Composting Council

(a trade and professional organization)
114 South Pitt Street
Alexandria, Virginia 22314
phone: 703-739-2402
fax: 703-739-2407

e-mail: ComCouncil@aol.com

http://CompostingCouncil.org

Woods End Agricultural Institute, Inc.

Rural Route #2, Box 1850
Mt. Vernon, Maine 04352
phone: 207-293-2453
fax: 207-293-2488

http://www.maine.com/woodsend/inst.htm

In New York:
285 Hungry Hollow Road
Chestnut Ridge, NY 10977
phone: 914-352-0145
fax: 914-352-0149

e-mail: info@woodsend.org

Websites:

A few web sites on composting:

Rot Web

Provides information on a variety of issues related to homecomposting. Includes a list of home composting publications andlinks to other sites.

http://www.indra.com/~topsoil/Compost_Menu.html

The Composting Resource Page

Provides access to information on composting from backyardto large scale systems. Includes an interactive bulletin boardfor questions and answers.

http://www.oldgrowth.org/compost

Home Composting

If you are a non-profit home composting group, this site willprovide a free web page for you and link it to their site. Alsoincluded: a list of organic materials with appropriate compostmethods for each, as well as instructions for building bins, compostingwith worms, and other composting methods.

http://www.mastercomposter.com

BioNet

Includes access to technical publications and a database ofwaste management sites, in German and English.

http://www.bionet.net/

Listserves:

Subscription information forthe interactive mailing list "Compost"

This listserve provides an ongoing discussion of issues relatedto composting. If you have a question, simple or complex, thechances are someone on the list has the answer and would be happyto help you out.

Leaf Mulching Discussion Group

An interactive resource for information, query, and discussion on leaf mulching, the application of noncomposted municipal leaves to farmland.

Publications:

BioCycle

Journal of Composting & Recycling
The JG Press, Inc.
419 State Avenue
Emmaus, PA 18049
phone: 610-967-4135

e-mail: biocycle@jgpress.com
http://www.jgpress.com

Composting News

Ken McEntee, Editor
13727 Holland Road
Cleveland, OH 44142
phone: 216-362-7979
fax: 216-362-6553

e-mail: mcenteemedia@compuserve.com
http://www.recycle.cc

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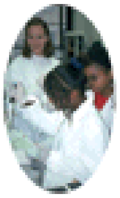
Science & Engineering



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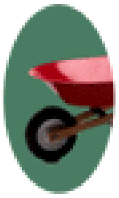

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App. A Characteristics of Raw Materials
Table A.1

Material	Type of value	% N (dry weight)	C:N ratio (weight to weight)	Moisture content % (wet weight)	Bulk density (pounds per cubic yard)
Crop residues and fruit/vegetable-processing wastes					
Apple filter cake	Typical	1.2	13	60	1,197
Apple pomace	Typical	1.1	48	88	1,559
Apple-processing sludge	Typical	2.8	7	59	1,411
Cocoa shells	Typical	2.3	22	8	798
Coffee grounds	Typical	-	20	-	-
Corn cobs	Range	0.4-0.8	56-123	9-18	-
	Average	0.6	98	15	557
Corn stalks	Typical	0.6-0.8	60-73 a	12	32
Cottonseed meal	Typical	7.7	7	-	-
Cranberry filter cake	Typical	2.8	31	50	1,021
(with rice hulls)	Typical	1.2	42	71	1,298
Cranberry plant (stems, leaves)	Typical	0.9	61	61	-
Cull potatoes	Typical	-	18	78	1,540
Fruit wastes	Range	0.9-2.6	20-49	62-88	-
	Average	1.4	40	80	-
Olive husks	Typical	1.2-1.5	30-35	8-10	-
Potato-processing sludge	Typical	-	28	75	1,570
Potato tops	Typical	1.5	25	-	-
Rice hulls	Range	0-0.4	113-1120	7-12	185-219
	Average	0.3	121	14	202
Soybean meal	Typical	7.2-7.6	4-6	-	-
Tomato-processing waste	Typical	4.5	11 a	62	-
Vegetable produce	Typical	2.7	19	87	1,585
Vegetable wastes	Typical	2.5-4	11-13	-	-
Fish and meat processing					
Blood wastes (slaughterhouse waste and dried blood)	Typical	13-14	3-3.5	10-78	-

Crab and lobster wastes	Range	4.6-8.2	4.0-5.4	35-61	-
	Average	6.1	4.9	47	240
Fish-breading crumbs	Typical	2.0	28	10	-
Fish-processing sludge	Typical	6.8	5.2	94	-
Fish wastes (gurry, racks, and so on)	Range	6.5-14.2	2.6-5.0	50-81	-
	Average	10.6	3.6	76	-
Mixed slaughterhouse waste	Typical	7-10	2-4	-	-
Mussel wastes	Typical	3.6	2.2	63	-
Poultry carcasses	Typical	2.4 b	5	65	-
Paunch manure	Typical	1.8	20-30	80-85	1,460
Shrimp wastes	Typical	9.5	3.4	78	-
Manures					
Broiler litter	Range	1.6-3.9	12-15 a	22-46	756-1,026
	Average	2.7	14 a	37	864
Cattle	Range	1.5-4.2	11-30	67-87	1,323-1,674
	Average	2.4	19	81	1,458
Dairy tie stall	Typical	2.7	18	79	-
Dairy free stall	Typical	3.7	13	83	-
Horse-general	Range	1.4-2.3	22-50	59-79	1,215-1,620
	Average	1.6	30	72	1,379
Horse-race track	Range	0.8-1.7	29-56	52-67	-
	Average	1.2	41	63	-
Laying hens	Range	4-10	3-10	62-75	1,377-1,620
	Average	8.0	6	69	1,479
Sheep	Range	1.3-3.9	13-20	60-75	-
	Average	2.7	16	69	-
Swine	Range	1.9-4.3	9-19	65-91	-
	Average	3.1	14	80	-
Turkey litter	Average	2.6	16 a	26	783

Municipal wastes					
Garbage (food waste)	Typical	1.9-2.9	14-16	69	-
Night soil	Typical	5.5-6.5	6-10	-	-
Paper from domestic refuse	Typical	0.2-0.25	127-178	18-20	-
Pharmaceutical wastes	Typical	2.6	19	-	-
Refuse (mixed food, paper, and so on)	Typical	0.6-1.3	34-80	-	-
Sewage sludge	Range	2-6.9	5-16	72-84	1,075-1,750
Activated sludge	Typical	5.6	6	-	-
Digested sludge	Typical	1.9	16	-	-
Straw, hay, silage					
Corn silage	Typical	1.2-1.4	38-43 a	65-68	-
Hay-general	Range	0.7-3.6	15-32	8-10	-
	Average	2.10	-	-	-
Hay-legume	Range	1.8-3.6	15-19	-	-
	Average	2.5	16	-	-
Hay-non-legume	Range	0.7-2.5	-	-	-
	Average	1.3	32	-	-
Straw-general	Range	0.3-1.1	48-150	4-27	58-378
	Average	0.7	80	12	227
Straw-oat	Range	0.6-1.1	48-98	-	-
	Average	0.9	60	-	-
Straw-wheat	Range	0.3-0.5	100-150	-	-
	Average	0.4	127	-	-
Wood and paper					
Bark-hardwoods	Range	0.10-0.41	116-436	-	-

	Average	0.241	223	-	-
Bark-softwoods	Range	0.04-0.39	131-1,285	-	-
	Average	0.14	496	-	-
Corrugated cardboard	Typical	0.10	563	8	259
Lumbermill waste	Typical	0.13	170	-	-
Newsprint	Typical	0.06-0.14	398-852	3-8	195-242
Paper fiber sludge	Typical	-	250	66	1140
Paper mill sludge	Typical	0.56	54	81	-
Paper pulp	Typical	0.59	90	82	1403
Sawdust	Range	0.06-0.8	200-750	19-65	350-450
	Average	0.24	442	39	410
Telephone books	Typical	0.7	772	6	250
Wood chips	Typical	-	-	-	445-620
Wood-hardwoods	Range	0.06-0.11	451-819	-	-
(chips, shavings, and so on)	Average	0.09	560	-	-
Wood-softwoods	Range	0.04-0.23	212-1,313	-	-
(chips, shavings, and so on)	Average	0.09	641	-	-
Yard wastes and other vegetation					
Grass clippings	Range	2.0-6.0	9-25	-	-
	Average	3.4	17	82	-
Loose	Typical	-	-	-	300-400
Compacted	Typical	-	-	-	500-800
Leaves	Range	0.5-1.3	40-80	-	-
	Average	0.9	54	38	-
Loose and dry	Typical	-	-	-	100-300
Compacted and moist	Typical	-	-	-	400-500
Seaweed	Range	1.2-3.0	5-27	-	-
	Average	1.9	17	53	-
Shrub trimmings	Typical	1.0	53	15	429
Tree trimmings	Typical	3.1	16	70	1,296
Water hyacinth-fresh	Typical	-	20-30	93	405

Note: Data was compiled from many references listed in the suggested readings section of this handbook (pages 179-180). Where several values are available, the range and average of the values found in the literature are listed. These should not be considered as the true ranges or averages, just representative values.

a Estimated from ash or volatile solids data.

b Mostly organic nitrogen.

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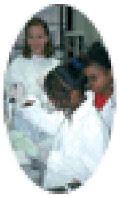
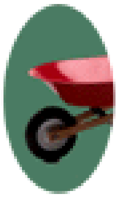
Cornell Composting


Science & Engineering


Composting in Schools


Resources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This page was created on January 26, 1996
This page was last updated on October 2000

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Back to the ***Effect of Lignin on Biodegradability***
Back to the ***C/N Ratio***

(Sources:)

Ingredient	Lig %	Cellulose (%)	Hemicellulose (%)	Nitrogen %	Ash %
(all data on a dry matter basis)					
Acorns	13	--	--	0	--
Alfalfa	7.5	24	8	2.72	
Meal dehydrated (dehy) 15%	13	23	14	2.56	10
Meal dehy 17%	10	25	10	2.72	11
Hay, early (E.) vegetative (veg.)	5.3	20.7	10	3.744	10
Hay, late (L.) veg.	6.5	21.5	11	3.472	10
Hay, E. bloom (bl.)	7.1	23.9	11	3.04	9
Hay, medium (M.) bl.	8.7	27.3	10	2.72	9
Hay, full (F.) bl.	10.4	30.6	10	2.08	9
Hay, L. bl.	12.2	30.8	12	1.92	8
Hay, E. veg.	6	19	8	4.8	10
Hay, L. veg.	7	20	10	4.32	9
Hay, E. bl.	8	22	10	4	9
Hay, M. bl.	10	25	9	3.52	8
Hay, F. bl.	11	26	11	3.04	8
Hay, L. bl.	12.2	26.8	14	2.72	8
Hay, mature	14.4	29.6	14	2.24	7
Hay, seeded	17	32	21	1.92	7
Hay, weathered	15	30	13	1.6	8
Wilted Silage					
E. bl. 35% dry matter (DM)	10	23	10	3.04	9
M. bl. 38% DM	11	24	12	2.72	9
F. bl. 40% DM	12	30	9	2.56	8
Almond Hulls, good	6.1	10.9	5	0	7
Medium quality	10	17	4	0	7
Molded	30	27	0	0	8
Apple pomace	5	--	--	< 0.5	--
Bagasse	18.9	33.4	30.0	--	2.4
Bagasse	11	38	34	--	--
Bahiagrass, 30% DM	7	31	30	1.424	10
Hay	8	33	31	1.312	11

Bakery Waste	1	12	5	1.44	5
Bamboo	20.1	--	19.6	--	3.3
Barley, Grain					
Heavy	2	5	12	2.08	3
Grain Light	2.9	7.1	18	2.24	4
Malt Sprouts w/hulls	3	15	28	4.496	7
Straw	11	48	21	0.688	7
Beet Pulp, dehy	2	31	21	1.232	5
+Steffen's filtrate	2	19	21	1.6	6
Bermudagrass	7	32	38	1.44	
Coastal Hay, L. veg.	6	26	38	1.6	8
Black pepper	18	--	--	1.28	--
Bloodmeal	--	--	--	14.672	7
Brewers, Grains, dehy	6	18	22	4.16	4
-Grains wet, 21% DM	4	19	19	4.16	10
Brome	5.5	27	15.3	--	--
Hay, Pre-bl.	5	33	27	1.68	10
Hay, L. bl.	8	36	28	1.184	9
Smooth, Hay M. bl.	4	33	29	2.336	10
Hay, mature	8	37	26	0.928	8
Canarygrass, Reed, Hay	4	32	28	1.648	10
Carrot Roots, fr. 12% DM	0	8	1	1.584	8
Cattails	8.5	--	--	2.176	--
Celery seed	22	--	--	2.4	--
Cinnamon bark	20	--	--	0	--
Citrus pulp, dehydrated	3	19	1	1.12	7
Clover, Ladino, Hay	7	22	7	3.52	10
Clover, Red, Hay	10	31	15	2.56	9
Cocoa bean	25	--	--	2.56	--
Coconut meal	10	--	--	3.44	--
Coffee Grounds	15	--	9	0	2
hulls (bran)	20	51	22	0	5
Corn					
Bran	1	15	44	1.76	3
Cobs, ground	7	28	55	0.512	2
Cob	-	36.5	28	--	--
Cob	7	--	--	0.48	--
Corn leaves	3.8	--	--	3.04	--
Corn meal	2	--	--	1.776	--
Distillers grain, dehy	5	12	33	4.16	4

wet	4	11	25	4.16	4
grains + solubles	4	12	28	4.72	5
solubles, dehy	1	6	16	4.752	8
Fodder	3	30	22	1.424	2.4
Gluten feed	1	11	33	4.096	5
Gluten meal	1	8	28	7.488	3
Gluten meal 60% crude protein	1	4	9	10.752	2
Grain cracked	0.2	2.8	6	1.6	2
Grain flaked	0.2	2.8	6	1.6	2
Grain ground	0.2	2.8	6	1.6	2
Grain high moisture	0.2	2.8	6	1.696	2
Hominy	2	11	42	1.84	1
Stover	11	28	28	1.056	7
Whole ear (corn & cob)	2	10	16	1.44	2
Corn Silage	3	26	16	1.44	
-45% grain	3	23	15	1.44	5
+NPN	3	23	15	2.08	5
+NPN + Ca	3	23	15	2.08	7
-35% grain	4	24	18	1.376	7
-25% grain	5	26	21	1.328	8
-40% grain	4	23	18	1.472	4
NPN	4	23	18	2.112	4
NPN + Ca	4	23	18	2.08	6
25% grain	6	27	22	1.328	7
Stalklage	7	38	23	1.008	9
Immature (25% DM no ears)	3	35	22	1.44	11
Cornstalk	11	38	26	--	3
Cornstalk	3.9	--	--	1.056	--
Cornstalk	11	33.5	32.6	--	1
Cotton	--	80-95	5-20	--	--
Cottonseed					
hulls	24	49	17	0.656	4
Black whole seed	15	16	9	3.68	5
high lint	16	21	10	3.2	4
seed meal, mech. ex.	6	14	8	7.04	7
Solv. 41% crude protein (CP)	6	13	7	7.296	7
Solv. 43% CP	7	14	7	7.824	7
Cotton straw	15	42	12	--	--
Distillers' grains	5	--	--	3.52	--

Feather meal	--	--	--	12.48	4
Fescue, Alta, Hay	6.5	34.5	29	1.632	10
Fescue, K31, Hay	4	31	28	2.624	9
Hay F. bl.	5	34	28	1.936	8
mature	7	35	28	1.472	7
Fescue, Meadow, Hay	7	36	22	1.456	8
Tall fescue	3.1	30	24.5	--	--
Fishmeal				10.656	25
Fruit pits	40	--	--	--	--
Ginger root	6	--	--	1.6	--
Grape pomace	17	--	--	0	--
Grape pomace	35	19	1	0	10
Grape stems	12	--	--	< 0.5	--
Guineagrass	8	35	26	1.44	
Kelp, treated	6	--	--	4.8	--
Linseed meal	7	--	--	4.48	--
mech. ex.	7	10	8	6.064	6
meal solv. ex.	6	13	6	6.128	6
Lupins	3.3	--	--	5.472	--
Manure					
Elephant manure	10.4	--	--	1.12	--
Chicken manure	3.4	--	--	5.424	--
Pig manure	2.2	--	--	4.416	--
Cow manure sample 1	8.1	--	--	3.104	--
Cow manure sample 2	7.9	--	--	3.216	--
Cow manure sample 3	10.1	--	--	2.752	--
Millet feed	4	13		2.064	3
Milo see sorghum					
Molasses beet,					
79% DM	0	0	0	0.48	11
Molasses cane,					
73% DM	0	0	0	1.28	8
Municipal refuse	--	76	--	--	--
Napiergrass fr.	8	36	28	1.44	
-30 days DM	10	35	25	1.392	9
-60 days DM	14	33	28	1.248	6
Needle and thread	6	37	40	0.656	20
Nutmeg hulls	17	--	--	0.16	--
Oats, grain gr.		0	0		
-38 lb/bushel	3	13	16	2.128	3

-32 lb/bushel	4	17	21	2.096	5
Hay	6	30	30	1.488	8
Hulls	8	34	36	0.624	7
Silage dough	9	23	24	1.6	7
Straw	14	33	23	0.704	8
Olive waste	28	--	--	0	--
Orchard grass	4.7	30	14.4	--	--
Orchardgrass, young	4.3	26	25	2.4	
Hay E. bl.	4	30	23	1.632	10
Hay, L. bl.	4	34	27	1.344	9
Palm kernel oil meala	14	--	--	0.24	--
Pangola grass	7	34	29	1.76	
fresh pangola grass, 21% DM	5	33	32	1.648	10
Paper Products					
Brown cardboard	12	72	--	--	1.7
Christian Science Monitor	21	60	--	--	0.4
Manchester Guardian	3	59	--	--	30
Newsprint	20.9	--	--	0.816	--
Playboy	9	51	--	--	24
Solka floc (cellulose)	5	84	--	--	0.3
Washington Post	26	55	--	--	0.4
Whatman no. 41	5	89	--	--	0.2
Pea vines, Silage, 25% DM	9	40	10	2.096	12
Peanut, Hulls	23	42	9	1.248	4
Meal	--	--	8	8.32	6
Peanut skin	7	--	--	< 0.5	--
Pineapple, bran	7	30	36	0.736	3
Potato tubers	1	1	4	1.424	6
Poultry, Manure	2	12	24	4.512	22
Pricklypear, fr. 17% DM	1	1	4	0.768	6
Rapeseed meal	3.7	--	--	6.768	8
Red Top, fr. 29% DM	8	32	24	1.856	8
Reed Canary grass	5.3	28	16.5	--	--
Reed foxtail	4.5	29	17.7	--	--
Rice					
bran	3.3	10.7	11	2.08	10
Grain, ground	2.1	--	--	1.424	5
Grain, polished	<1	<1	--	1.376	1
hulls	17	55	10	0.48	20

straw	12.5	32.1	24.0	--	17.5
Russian Thistle,	11	33	20	1.792	15
Rye grain	1	--	--	2.208	2
Ryegrass, Hay	2	28	11	1.376	10
Ryegrass, Straw	5	37	27	--	--
Safflower, Meal					
mech. ex.	14	27	18	3.536	4
meal solv. ex.	14	27	17	4.064	4
Sagebrush, Big s.c.	12	18	12	1.488	7
Sesame seed	2	--	--	--	--
Sorghum, Grain dry (milo)	1.4	3.6	18	1.984	2
Grain rolledb	1.4	3.6	18	1.984	2
Grain, steam flaked	1.4	3.6	18	1.92	2
-Silage, 30% DM	6	32	26	1.2	9
Soybean, Hulls	2	48	17	1.936	5
Soybean meal -44	0.3	9.7	4	7.84	7
Soybean meal -49	0.2	5.8	2	8.8	7
Soybean Straw	16	38	16	0.832	6
Soybean whole	0.2	8.8	4	6.848	6
Sudangrass, Hay	4	35	27	1.808	10
-Silage, 28% DM	5	37	29	1.728	10
Sugar beet pulp	5	--	--	1	--
Sunflower					
Sunflower hulls	19	--	--	--	--
Sunflower meal	12	21	7	4.144	6
Tapioca	--	--	--	0.496	3
Timothy					
Timothy, mature	7.3	31	29	1.12	
Hay L. veg.	3	27	25	2.24	8
Hay, E. bl.	4	30	27	1.76	7
Hay, M. bl.	5	31	31	1.44	7
Hay, L. bl.	6	34	28	1.28	7
Hay, Milk st.	7	36	28	1.12	6
Hay, seed st.	9	36	27	0.96	6
-Silage, L. bl. 42% DM	7	34	24	1.44	7
Tomato					
Tomato pomace, dried	11	39	5	2.56	8
Tomato vines	-	--	--	--	--
Trefoil, birdft., Hay	9	27	11	2.608	7
Turnip, fr. 9% DM	10	24	10	1.888	2

Urea	0	0	0	46.72	0
Vanilla bean	14	--	--	0	--
Vetch, Hay	8	25	15	3.328	7
Water hyacinth	8.7	--	--	2.832	--
Wheat					
bran	3	12	36	2.736	7
Grain, Hard red spring	1	4	11	1.808	2
Grain, soft white	0.6	3.4	10	1.808	2
Hay, E. veg.	4	26	22	1.92	8
Hay, headed	7	34	27	1.36	7
Middlings	2.2	8.8	26	2.944	2.4
Silage dough	7.7	25.3	19	1.296	8
Straw	8.9	--	--	1.488	--
Straw	14	40	31	0.576	8
Straw	18.0	30.5	28.4	--	11.0
Straw	18	34	27.6	--	1.3
Straw	7	42	31	--	--
Wheatgrass crest., Hay	6	30	29	1.44	9
Whey, Acid	--	--	--	2.272	10
Delact.	--	--		2.864	17
Winterfat, s.c.	10	34	28	1.728	15
Wood					
Aspen	15.5	50.8	28.7	--	0.2
Balsam Fir	28	42.7	24.4	--	0.2
Beech	12.7	27.7	21.1	1.44	--
Birch	19.5	38.8	37.3	--	0.3
Birch	19.5	40.0	39.0	--	0.3
Pin cherry	8.98	8.77	8.4	1.77	--
Pine	27.8	44.0	26.0	--	0.4
Pine	27.8	42	23.5	--	0.4
Pine kraft pulp	5.0	77.0	18.0	--	0.4
Red maple	23	39	33	--	0.2
Spruce	28.6	42	26.5	--	0.4
Spruce	28.6	43.0	27.0	--	0.4
Sugar maple	8.49	14.1	9.95	0.97	--
Yellow birch	12	17.3	13.2	1.42	--

Sources:

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Calculate C/N Ratio For Three Materials

This calculation solves for the carbon to nitrogen ratio of up to three materials. Enter the mass of each material (wet weight), percentage of carbon, percentage of nitrogen, and percentage of moisture, then click on the calculate button. If you have less than three materials be sure to enter zeroes in the fields for the missing materials.

Note - Use whole numbers

Ingredient	% H20	Weight	% Carbon	% Nitrogen	C/N Ratio
				Result:	

Reset

Here's the Formula:
Given overall moisture percentage goal of (g)

Ingredient	%H20	Weight	%Carbon	%Nitrogen	C/N Ratio
1	M_1	Q_1	C_1	N_1	
2	M_2	Q_2	C_2	N_2	
3	M_3	Q_3	C_3	N_3	
					R

$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3) + \ldots}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3) + \ldots}$$

```
in which:
        R = C/N ratio
        Qn = mass of material n ("as is", or "wet weight")
        Cn = carbon (%)
        Nn = nitrogen (%)
        Mn = moisture content (%) of material n
```

Calculate Percent Moisture of Compost

In this example, you can calculate the moisture content in compost, given three ingredients, their individual moisture contents and their individual weights.

Enter the percentages and weights below and then click on the calculate button to get the result. To solve for less than three ingredients enter zeroes in rows where ingredient is missing.

Ingredient	% H20	Weight	
		Solve for % Moisture:	

Reset

Here's the Formula:

Ingredient	%H20	Weight
	a	x
	b	y
	c	z

```
% Moisture(H20) = ((a*x) + (b*y) + (c*z)) / (x + y + z)
```

Calculate Required Weight of Third Ingredient for Ideal Moisture Content

This calculation solves the moisture equation for the required weight of a third ingredient to balance the first two and achieve your moisture goal. Enter the moisture goal, percentages of water, and known weights below and then click on the calculate button to get the result. If you have only two ingredients be sure to enter zeroes in the fields for the missing ingredient.

Note - There is an unresolved rounding error with this software. Please enter whole numbers for all inputs, and the results should be correct.

Ingredient	% H20	Known Weight	Unknown Weight
Enter Moisture Goal (%):		Calculate for Weight of Third Ingredient:	

Reset

Here's the Formula:
Given overall moisture percentage goal of (g)

Ingredient	%H20	Known Weight	Unknown Weight
	a	x	
	b	y	
	c		z

Required weight of third ingredient (z) = $((g * x) + (g * y) - (a * x) - (b * y))/(c - g)$