The Science and Engineering of Composting
Compost Engineering Fundamentals

Cornell Authors:
Dr. Nancy M. Trautmann - Cornell Department of Natural Resources
Dr. Tom Richard - formerly at the Cornell Department of Agricultural and Biological Engineering
Dr. Marianne E. Krasny - Cornell Department of Natural Resources

Teacher Authors:
Patrick Cushing - formerly at Boys & Girls High School, Brooklyn, NY
Stephanie Hyson - Boys &Girls High School, Brooklyn, NY
Richard Northrup - Waterloo High School, Waterloo, NY
Elaina Olynciw - A. Philip Randolph High School, New York City, NY
Barbara Poseluzny - A. Philip Randolph High School, New York City, NY

Scientific Advisors:
Dr. Joe Regenstein - Cornell Deparment of Food Science
Dr. Erin McDonnell - formerly at Cornell Deparment of Food Science
Dr. Eric Nelson - Cornell Deparment of Plant Pathology
Dr. Larry Walker - Cornell Dept. of Agricultural and Biological Engineering

Compost Engineering Fundamentals
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 CO_2 and H_2O. For a completely mixed reactor, the ash and volatile solids percent of a sample and the original mass data can be used to calculate the volatile solids mass remaining using the following equation:

$$VS_{Mt} = VS_{Mo} \frac{Ash\%_o \times VS\%_t}{Ash\%_t \times VS\%_o}$$

where

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

VS_{Mo} = 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):

$$TS_{Mt} = TS_{Mo} - \left(VS_{Mo} - VS_{Mt} \right)$$

where

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

TS_{Mo} = the initial mass of total solids

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

VS_{Mo} = 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 H_2O 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

$$(\Delta H_2O)_\% = 100\left[1 - \left(\frac{100 - VS_{\%_0}}{100 - VS_{\%_t}}\right) \times \left(\frac{H_2O_{\%_t}}{H_2O_{\%_0}}\right) \times \left(\frac{100 - H_2O_{\%_0}}{100 - H_2O_{\%_t}}\right)\right]$$

where

$(\Delta H_2O)_\%$ = percent reduction in H_2O at time t

Acknowledgement:

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 buoyancy 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

Tom Richard

Diffusion reflects 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:

$$\frac{\partial c_A}{\partial t} = D_{AB} \nabla^2 c_A \tag{1}$$

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:

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

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. 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 O_2 diffusion coefficient in saturated air (at 15% O_2 concentration) is 5700 to 10,800 times greater than in water (at 60°C and 20°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.

Reference

Bird, R.B., W.E. Stewart, and E.N. Lightfoot. 1960. Transport Phenomena. John Wiley & Sons. NY. 780 pp.

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):

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

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, kT/ε_{AB} ranges from about 1.3 to 3.5. Using tabulated values for k/ε_A for each of the gases in the mixture (see Table 1), k/ε_{AB} was calculated for each binary pair according to the square root rule:

$$\varepsilon_{AB}/\kappa = \sqrt{\varepsilon_A/\kappa} + \sqrt{\varepsilon_B/\kappa} \tag{2}$$

Source: Welty et al., 1984

The collision integral Ω can be approximated from tables relating it to kT/ε_{AB}. For the kT/ε_{AB} values of interest Ω ranges from about 1.3 to 0.9 (decreasing as kT/ε_{AB} increases). For this series of calculations a 5th order polynomial was fit to the kT/ε_{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 Mixtures of Gases

Binary Pair	Temp (°C)	ε_A/κ (°K)	Diffusion coefficient (cm²/sec)
Oxygen-Carbon dioxide	20	146	0.153
	60		0.193
Oxygen-Water vapor	20	201	0.240
	60		0.339
Oxygen-Nitrogen	20	102	0.219
	60		0.274

Mixture of Gases

While air has relatively uniform constituency (except for 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. 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

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

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

Temperature (ºC)	Relative Humidity (%)	Oxygen Coefficient (cm²/sec at 2% O₂)	Oxygen Coefficient (cm²/sec at 15% O₂)
20	50	0.203	0.214
20	100	0.203	0.214
60	50	0.259	0.273
60	100	0.264	0.278

From the results in Table 2 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:

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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

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

water = 2.26 (Reid et al., 1977). $\mu =$ viscosity of water, in centipoises (see table 1)

V_{O_2} = the molar volume of oxygen = 25.6 cm3/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 $\pm$ 10% for dilute solutions of non-dissociating 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 above.

Table 3. Effect of Temperature and Viscosity on the Oxygen Diffusion Coefficients in Water

Temperature (ºC)	Viscosity of H_2O (centipoises) (Weast, 1969)	Oxygen Diffusion Coefficient (cm^2/sec)
20	1.002	0.0000197
40	0.653	0.0000324
50	0.547	0.0000399
60	0.467	0.0000482

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:

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

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:

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

where

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

σ = surface tension of fluid against air

(for water, $\sigma = 0.073$ 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, $\rho = 998$ 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 $h\rho g = -\Psi_m$ (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 4 gives the critical air-filled pore radius at a given -98.9   0.00136moisture content. Pores larger than this critical dimension remain largely air filled, while smaller pores are filled with water.

Table 4. 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	-0.03	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 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.

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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 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 management 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 Inocula

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. Several 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 may also be required, particularly in sensitive neighborhoods.

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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 many 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.

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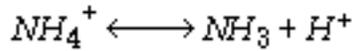
$$\frac{\left[NH_3\right]\left[H^+\right]}{\left[NH_4^+\right]} = 5.7 \times 10^{-10}$$

Source: Sawyer and McCarty, 1978)

A plot of this equation, showing the relative concentrations of NH_3 and NH_4^+, is provided below.
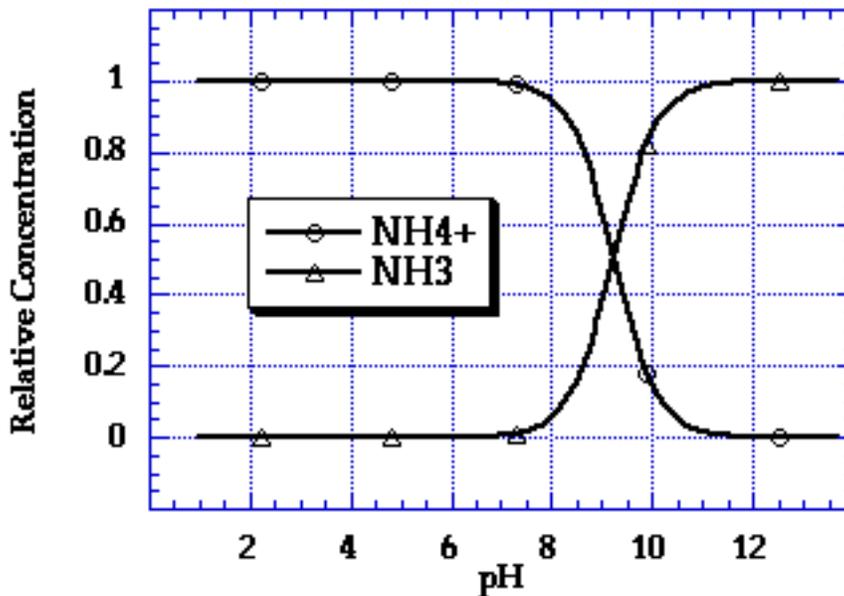
In a real composting system this equilibrium relationship would have to be corrected somewhat if there are other ions in solution, or if the compost is at a temperature other than 25°C.

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.

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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 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 cm2/sec to 0.28 cm2/sec.

While the diffusion coefficient can vary depending on the conditions in the gas phase, even more dramatic effects are seen when the oxygen must diffuse through water rather than air. In water at 60°C, the oxygen diffusion coefficient is approximately 4.8 x 10-5 cm2/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

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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.
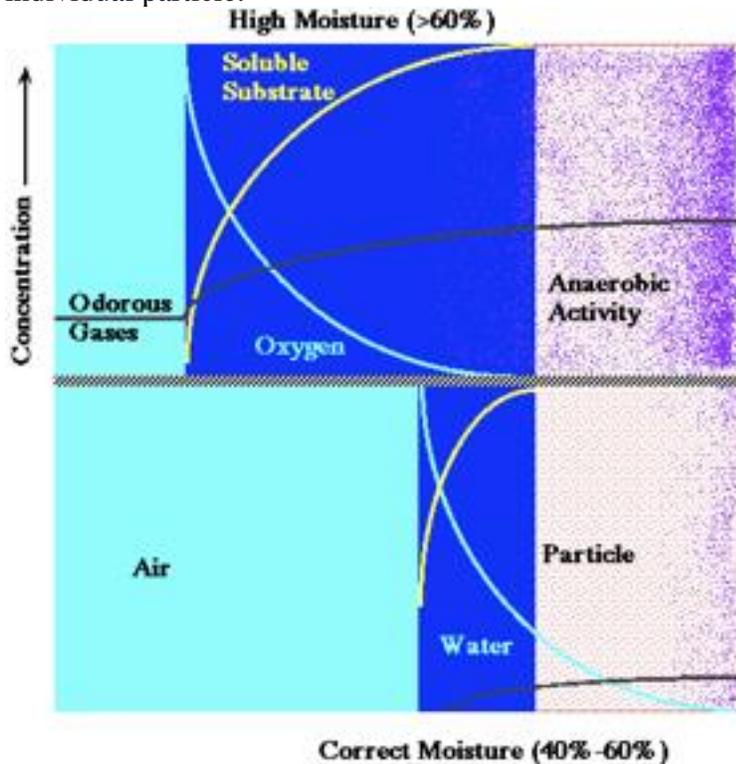

Figure 1. The effect of aqueous film thickness on anaerobic odor production.

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

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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.
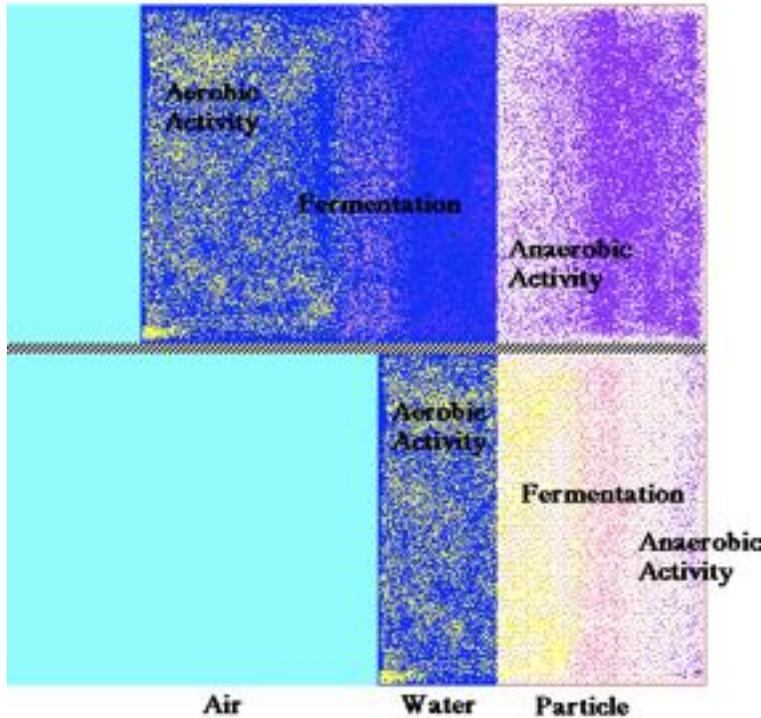

Figure 2. Metabolic Regions as a function of moisture content.

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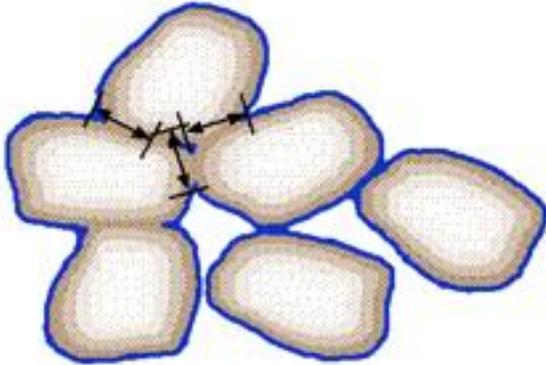
Figure 3. In a properly moist compost matrix, the particles (brown) are surrounded by aqueous films (blue) but are separated by air filled pores (white).

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
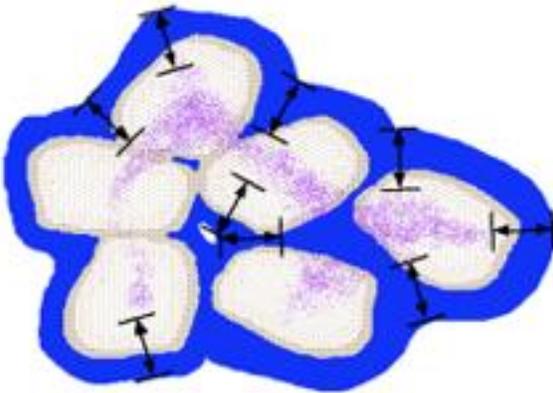

Figure 4. Anaerobic zones (purple dots) are created as increasing water content fills small pores, so oxygen must diffuse farther through water.

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.

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:
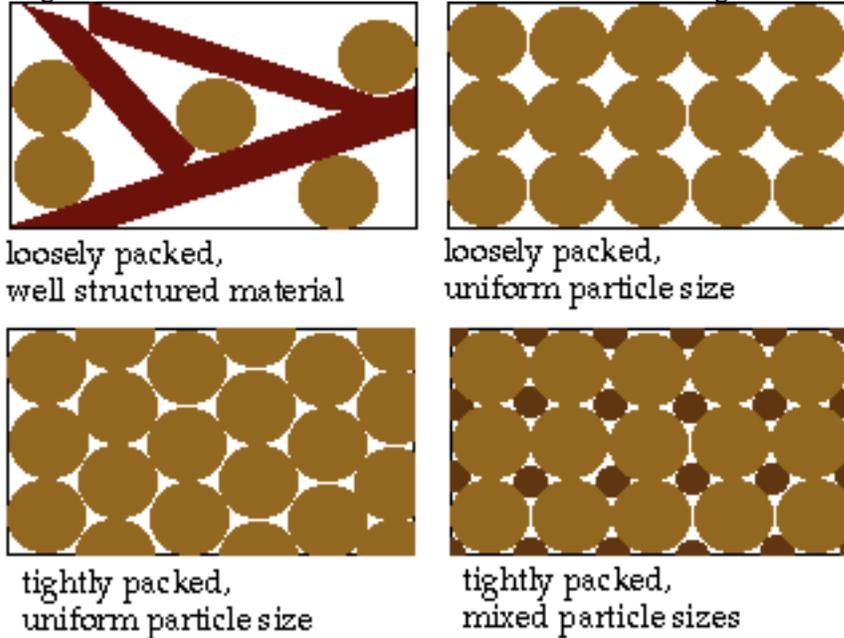

loosely packed,
well structured material

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 effective $= S^2$ x D

Where:

$D_{effective}$ = 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

Papendick, R.I., and Campbell, G.S. 1981. Theory and measurement of water potential. pp 1-22. In: Water Potential Relations in Soil Microbiology. SSSA special publication No. 9. J.F. Parr, W.R. Gardner and L. F. Elliott, (eds.). Soil Science Society of America: Madison, Wis. U.S.A.

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.

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.

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/ft²) and are typically

0.015 to 0.02 m/s (3 to 4 cfm/ft²). 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:
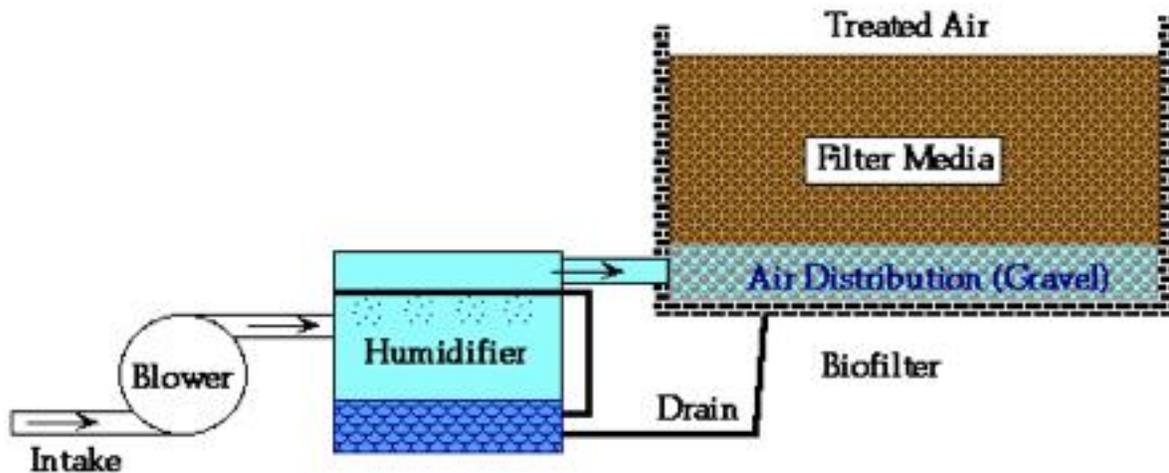
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Water Quality Protection
Tom Richard

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.

Several 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 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 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 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 dependent 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 one 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 affect 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.

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