Comparison of the Environmental Effects of Aerobic and Anaerobic Composting Technologies

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INTRODUCTION

The biological conversion of yard wastes and municipal solid waste by aerobic composting is an established technology. Anaerobic conversion of these wastes is less practiced but is being widely advocated for the next generation of bioconversion systems. Although the operational characteristics of both types of systems is well known, there is a lack of quantifiable data in the literature on the environmental effects of these technologies. It is widely assumed that they are environmentally benign, especially as compared to other processing and conversion technologies such as incineration or mechanical processing.

The process microbiology, design, and operational characteristics of aerobic and anaerobic composting systems are compared and contrasted in this paper. Environmental effects such as odor and VOC emissions, pathogen destruction, energy and water consumption will be evaluated. Environmental impacts which may arise from the usage of compost off-site such as heavy metal uptake by plants will not be discussed.

AEROBIC COMPOSTING PROCESSES

Aerobic biological conversion processes utilize oxygen in the conversion of organic materials. The end products of the conversion are new cells, CO_2, water, SO_4^{-2}, NH_3 and heat, and humus or compost. The primary rationale for operating such systems is both the production of compost, as well as the reduction in mass of organic waste materials.

Microbiology

Aerobic composting is accomplished by a complex mixture of naturally occuring microorganisms including bacteria, fungi, yeasts, and actinomycetes. If the complete conversion of organic waste to end products is assumed, then the oxygen requirement can be estimated by Equation (1) as follows[1] :

$$C_aH_bO_cN_d + \left(\frac{4a + b - 2c - 3d}{4}\right)O_2 \rightarrow aCO_2 + \left(\frac{b - 3d}{2}\right)H_2O + dNH_3 \qquad (1)$$

where

$C_aH_bO_cN_d$ = molar composition of the organic waste

The use of Equation (1) provides a conservative estimate of the oxygen required as bioconversion to end products is less than 100 percent. The degree of bioconversion obtainable can be estimated by calculating the biodegradeable fraction[2] of the solid waste using Equation (2):

$$BF = 0.83 - 0.028 \, LC \qquad (2)$$

where

BF	= biodegradeable solids fraction expressed on a volatile solids (VS) basis
0.83	= emperical constant
0.028	= emperical constant
LC	= lignin content of VS as a percent of dry weight

Biodegradeability fractions range from 0.22 for newsprint up to 0.82 for food wastes.

Technology

There are three principal systems for aerobic composting:

- Windrow composting - wastes are spread in long rows and periodically mechanically turned.

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- Aerated static pile composting - waste is formed into large piles and oxygen is added by forced aeration from a blower and manifold system.

- In-vessel composting - waste is processed in a vessel or reactor which is mechanically mixed to aerate the waste. Additional oxygen is sometimes added through forced aeration.

The microbiology of the three systems is identical, only the method of adding oxygen differs.

Environmental Requirements
The environmental requirements for aerobic composting include:

- Moisture content in the range of 50 to 60 percent.

- Particle size less than 2 inches

- Carbon to nitrogen (C:N ratio) by weight in the range of 20 to 25 to 1

Because most waste materials do not naturally match these requirements, blending of materials is usually required. C:N ratios and moisture contents for common wastes can be found in References 1 and 3.

Environmental Impacts of Aerobic Composting
Aerobic composting systems have a number of environmental impacts including:

- Odor and VOC emissions

- Pathogens

- Water consumption

- Energy consumption

- Surface runoff

These impacts and their remediation are discussed below.

Odor and VOC Emissions. Odor and volatile organic compound (VOC) emissions from aerobic composting are a natural consequence of the aerobic and anaerobic biodegradation of organic materials. Anaerobic conditions can develop in aerobic compost systems due to insufficient mixing or aeration. Representative odorous compounds associated with aerobic composting are presented in Table 1.

Odor panels and instruments such as the direct reading olfactometer can be used to identify and quantify the odor[4]. Several technologies are available for odor control in aerobic composting[5] including:

- Improved aeration and mixing.

- Biofiltration using compost and/or soil.

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- Activated carbon adsorbtion.

- Wet scrubbing with acid solutions, hydrogen peroxide, or various proprietary scrubbing solutions.

- Dilution with excess exhaust air.

- Dispersion with tall stacks.

Only the first technique is applicable to windrow compost systems. Static pile and in-vessel composting systems can also use the other control technologies because the exhaust air can be captured and ducted to an odor emission control system.

Pathogens. Pathogenic microorganisms such as bacteria, fungi, and parasites may be introduced into compost systems from wastewater sludges, and organic wastes found in municipal solid waste. Pathogens can be controlled by two methods: high temperatures, and reduction in moisture content. Because the aerobic composting process is exothermic, maintaining high temperatures for pathogen destruction is relatively easy. The EPA has defined temperature and time requirements for pathogen destruction as summarized in Table 2. Further pathogen destruction can be achieved by drying the compost to reduce its moisture content below 25 percent[6].

Water Consumption. The optimum moisture content for aerobic composting is 50 to 60 percent. Typical yard waste contains up to 60 percent moisture while typical municipal solid waste may only contain about 20 to 25 percent moisture content. Thus, depending on the original moisture and the composition of wastes being composted, additional water may need to be added at the beginning of the composting process. Water losses during composting occur due to evaporation which is accelerated by the relatively high temperatures achieved during aerobic composting. The water that is evaporated must be replaced during the active composting process to maintain the proper moisture level. In arid and semi-arid climates such as in parts of the southwestern U.S, this additional water requirement can significantly affect composting project economics unless lower-cost reclaimed water can be utilized. Data on the moisture content of the various wastes used in composting can be found in Reference 1 .

In the case of sludge composting, where moisture contents may be as high as 75 to 80 percent (or 25 to 20 percent solids content), dry amendments such as wood chips and sawdust are added to sludge to reduce moisture and add porosity. Amendments also add additional carbon to modify the C:N ratio of wastewater sludges. References 4 and 7 discuss water balances in sludge composting in detail.

Energy Consumption. The primary energy usage in aerobic composting is to provide aeration of the compost. Secondary usage is in materials handling to move the compost from one part of the process to another. A third energy usage in aerobic composting is in the front end processing of the wastes prior to composting. A final use of energy is in post processing to prepare the compost for marketing. Any energy comparison of composting systems or alternatives should account for all four forms of energy usage.

Aeration. Windrow systems are turned once or twice a week to provide aeration with either a front end loader or a specially designed compost turning machine. The use of compost turning machines is preferred as it is more efficient and will perform a more uniform mixing of the compost. Typically these machines have 200 hp diesel engines.

In aerated static pile systems and some in-vessel systems, aeration is by centrifugal blowers. This is the most energy efficient method of aeration because the degree of aeration can be controlled precisely by monitoring the temperature rise in compost. Typical blowers are powered by small electric motors in the 5 to 50 hp range.

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In-vessel systems use a variety of mechanical methods to mix and thus aerate the compost. The energy efficiency of these systems varies widely.

Materials Handling. Windrow and aerated static systems are initially prepared by using a variety of construction equipment including trucks, and front end loaders. Similar equipment is used to take down the piles after composting.

In-vessel systems have the most automated materials handling. Compost is typically moved in the systems by a variety of conveyor belts, chutes, and augers. This technique is potentially the most energy efficient but is also the most mechanically complex system for material handling.

Front-End Processing. Energy requirements for front end processing are similar for all three aerobic composting systems, but depend on the type of waste material being processed. For example, sludge requires the least processing, essentially mixing with an amendment such as wood chips. After composting, the wood chips are typically screened out of the compost and recycled. Yard waste requires shredding, typically in a tub grinder, and some screening prior to composting. Municipal solid waste (MSW), requires the most complex and energy intensive front end processing, with shredding, screening, and magnetic separation typically required.

Post Processing. Depending on the ultimate market for the compost, varying amounts of post processing may be required. For example, screening to remove residual glass, metals, and other impurities will usually be required. Some composts are upgraded by blending with fertilizers or mulches. In general, energy requirements for these activities will be minor compared to the energy requirements for aeration and front end processing.

Surface Runoff. Composting activities conducted in the open such as windrow and aerated static pile composting have the potential to generate surface runoff from precipitation and from excess water applied for moisture control. With proper drainage design, some of the runoff water can be recycled for moisture control of the compost itself. However, depending on rainfall, provisions should be made for capturing the runoff and treating it if required by local water quality regulations.

ANAEROBIC COMPOSTING PROCESSES

Anaerobic biological conversion processes utilize anaerobic bacteria to convert organic materials. The end products of the conversion are new cells, CO_2, CH_4, NH_3, H_2S, and humus or compost. Because CH_4, a combustible gas, can be recovered, anaerobic composting systems offer the potential of lower costs than aerobic composting systems.

Microbiology
Anaerobic biological conversion is accomplished by a complex three step process:

- One group of anaerobic bacteria is responsible for hydrolyzing organic polymers and lipids to basic structural building blocks such as monosaccharides, amino acids, and related compounds.

- A second group of anaerobic bacteria ferments these hydrolysis products into simple organic acids, the most common of which in anaerobic digestion is acetic acid. These bacteria are sometimes known as acidgens or acid formers.

- A third group of bacteria converts the hydrogen and acetic acid formed by the acidogens to methane gas and carbon dioxide. These bacteria are known as methanogens or acid formers.

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If complete bioconversion is assumed, Equation 3 can be used to estimate gas production[1]:

$$C_aH_bO_cN_d + \left(\frac{4a - b - 2c + 3d}{4}\right)H_2O \rightarrow$$

$$\left(\frac{4a + b - 2c - 3d}{8}\right)CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right)CO_2 + dNH_3 \tag{3}$$

where

$C_aH_bO_cN_d$ = molar composition of the organic waste

Technology
There are three primary systems for anaerobic composting:

- Low-solids digestion - organic wastes are processed in a sealed digester heated to between 30 to 38 °C (mesophyllic operation) or 55 to 60 °C (thermophyllic operation). Solids content is maintained at a low value of 4 to 8 percent.

- High-solids digestion - organic wastes are processed in a sealed, heated digester at mesophyllic or thermophyllic temperature ranges. Solids content is maintained at 20 to 35 percent.

- Combined high-solids anaerobic/aerobic composting - a two stage system which employs both a high solids anaerobic stage and an in-vessel aerobic stage has also been developed.

Low-solids digestion is widely used throughout the world for the processing and stabilization of sewage sludge. A number of pilot studies applying low-solids digestion to solid waste have not proven successful. The major problem was the dewatering and drying of the 4 to 10 percent slurry used in the digester to an acceptable 30 percent moisture content for application of the resultant compost[1].

High-solids digestion and the combined high-solids anaerobic/aerobic composting process offer considerable potential for future development. A number of pilot systems of both types are in operation throughout the world[1,8].

Environmental Requirements
The environmental requirements for anaerobic composting with respect to C:N ratio and particle size are similar to aerobic composting. Moisture content requirements range from 90 to 96 percent (low-solids) to 70 to 80 percent (high-solids).

Environmental Impacts
The environmental impacts of anaerobic composting are similar to those for aerobic composting and include:

- Odor and VOC emissions

- Pathogens

- Water consumption

- Energy consumption

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Odor and VOC Emissions. Although anaerobic composting systems are by definition closed systems, the potential for odors and VOC emissions exist from two sources: fugitive emissions and curing of the final compost product.

Fugitive emissions can arise during feeding and emptying processes or from leaks in the gas lines. Malodorous compounds most likely to be present in anaerobic systems include mercaptans and hydrogen sulfide (see Table 1). Because the biogas generated is a combustible mixture of CH_4 and CO_2, biogas, burning the biogas in a piston engine or gas turbine is essentially a high temperature combustion process which effectively destroys odorous compounds.

Usually H_2S is removed by scrubbing the biogas or reacting it with steel wool to reduce corrosion in the engine or turbine. Smaller systems can use flares to dispose of the biogas, although this will of course discard the energy content of the biogas. The use of biogas in turbines, engines, and flares is a well developed technology with off the shelf units available from a number of vendors[1,4].

Curing of compost involves removing it from the composting system and placing it in static piles for several weeks or months. The purpose of curing is to air dry the compost and to allow biological activity to cease. Odorous compounds could potentially be emitted during the curing phase. If objectionable odors are produced, curing may need to be done in an enclosed building with odor controls on exhaust air as discussed for aerobic composting. The combined anaerobic/aerobic composting process eliminates this problem because the aerobic stage completely stabilizes the organic waste to the maximum extent possible. If required, odor control measures can be applied to the exhaust air from the aerobic stage.

Pathogens. Concerns about pathogens in anaerobic composting are similar to those in aerobic composting. Given the long detention time (10 to 30 days) and high temperatures of anaerobic systems (30 to 38 °C for mesophillic systems and 55 to 60 °C for thermophillic systems), significant pathogen reduction will occur during the anaerobic composting process. Curing and drying of the resultant compost will further reduce pathogens.

Water Consumption. Initial water usage in anaerobic composting systems is higher than aerobic composting systems because of the necessity to operate at high moisture contents, 90 to 96 percent (low solids anaerobic composting) to 70 to 80 percent (high solids anaerobic composting).

Because anaerobic systems are sealed, it is not necessary to add water during the composting process. However, because of the high water content, the resultant compost must be first dewatered and then cured before use. Dewatering adds an extra cost element which must be considered. In the combined aerobic/anaerobic system, the aerobic stage effectively dewaters and dries the compost producing a biologically stable, dry, product.

Energy Consumption. Anaerobic composting systems are net producers of energy if a system boundary is drawn around the composting system not including front-end processing or materials handling. Electricity generally is the most practical form of energy recovery. Biogas can also be scrubbed to remove CO_2, compressed and used to fuel vehicles modified for compressed natural gas.

CONCLUSIONS

Both anaerobic and aerobic composting systems have environmental impacts that need to be considered as part of the solid waste management planning process. The principal environmental effects of both types of composting systems include:

- Odors and VOC emissions

- Pathogens

- Water consumption

- Energy consumption

- Surface runoff

All of these environmental impacts can be remediated with available technology. Although aerobic composting systems are currently the most widely used, anaerobic systems have the potential for lower environmental impacts and lower energy consumption.

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Table 1. Typical Odorous Compounds Associated with Aerobic Composting.[1]

| Compound | Chemical Formula | Odor, Quality | Odor Threshold, ppmV | |
			Detection	Recognition
Ammonia	NH_3	Ammoniacal	17.0	37.0
Diamines	$NH_2(CH_2)_4NH_2$ $NH_2(CH_2)_5NH_2$	Decayed Flesh	---	---
Ethyl Mercaptan	CH_3CH_2SH	Decayed Cabbage	0.0003	0.001
Hydrogen Sulfide	H_2S	Rotten Egg	<0.0002	0.00047
Methyl Amine	CH_3NH_2	Fishy	4.7	---
Methyl Mercaptan	CH_3SH		0.0005	0.001

[1] Adapted from Reference 4

Table 2. EPA Requirements for Pathogen Control in Compost Processes.[1]

Requirement	Description
Processes to significantly reduce pathogens (PSRP)	For in-vessel, aerated static pile, or windrow composting methods, compost must be maintained at a minimum temperature of 40°C for 5 days, including 4 hours at > 55°C.
Processes to further reduce pathogens (PFRP)	For in-vessel or aerated static pile composting methods, compost must be maintained at a minimum temperature of > 55°C for 3 days.
	For the windrow composting method, compost must be maintained at a minimum temperature of > 55°C for 15 days during the composting period. There will also be a minimum of 5 turnings of the windrow during this period.

[1]Adapted from References 1 and 9

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