Contractor's Report to the Board

Comprehensive Compost Odor Response Project

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Executive Summary

In 2004, the California Integrated Waste Management Board (CIWMB) initiated a project in partnership with San Diego State University to develop solutions to odor complaints plaguing an increasing number of facilities. The project, known as the Comprehensive Compost Odor Response Project, or CCORP, is a multi-facetted project that seeks to provide odor-management tools to local enforcement agencies (LEA) and to composting facility operators. The hope is that these tools will help prevent and positively resolve conflicts between facilities and the neighboring communities without closing or impairing composting operations. CCORP included a research component that developed mitigation strategies to control the generation and/or emissions of common odorous compounds during composting.

The work in this project was split into five components:

1. Literature review: summarized the published literature related to odor impacts from composting facilities and provided information in anticipation of preventing and resolving potential odor problems.
2. Odor assessment: identified the conditions leading to odor issues. A list of ten facilities which were known to have odor issues was prepared, and the factors contributing to the issue were identified.
3. Mitigation alternative research: various odor mitigation alternatives, which were chosen by the experts based on their practicality, ease of implementation, cost and chance of success were studied for a select set of targeted malodorous compounds.
4. Mitigation strategy menu: a set of mitigation alternatives were identified for a set of odorous compounds associated with different processing on a site.
5. Local government guide: a concise summary of the principles and planning considerations was prepared to be used by local government decision makers in early states of planning.

A Literature Review:
Generation, Measurement, and Mitigation of Odors from Composting Facilities

Preface

This report is a summary of published literature relating to odor impacts from composting facilities. It documents current knowledge of the subject in support of the Comprehensive Compost Odor Response Project (C-CORP), a cooperative project of the California Integrated Management Board (CIWMB) and San Diego State University (SDSU). The purpose of C-CORP is to provide odor-management tools to local enforcement agencies (LEAs) and to compost facility operators.

The hope is that these tools will help reduce and positively resolve conflicts between facilities and the neighboring communities without closing or impairing composting operations. C-CORP aims to elevate the conversation and respond to a level that reflects the complexity of composting odors. Thus, with these tools, an LEA and the facility operators might be better prepared to determine the cause and corrective action for an odor complaint. C-CORP also aims to provide information of a preventative nature that will avoid problems resulting from improper siting or poor selection of process or management components.

The first of C-CORP's tools is an assessment of the present state of composting odor science and management. This report delivers that assessment, primarily with LEAs and facility operators in mind. However, other public officials, and the public at large, should find the information useful as well. The report is intended to provide an information basis for understanding, anticipating, preventing and resolving potential odor problems associated with a compost facility. It is a starting point, bringing interested parties to the current state of knowledge.

Introduction

Odor is generally recognized as *the* critical issue for composting. Odor has been called composting's "Achilles heel" (Wilmink and Diener, 2001), a "thorn" in the side this otherwise environmentally-friendly pursuit (Haug, 1993) and "the issue" in public acceptance of composting facilities (McGinley and McGinley, 2005) and the "number one reason" for the closure of facilities (Cotton, 2005). More than any other factor, odor stands in the way of widespread adoption of composting and the many benefits that accompany composting and compost use.

It was once commonly believed that the presence of odors signaled a "problem" at the composting facility. The premise for this belief was that composting, a natural aerobic biological process, does not generate odors *when properly practiced*. The logic was – "if there is an odor, then something has gone wrong with the process." This paragon still persists in some circles. However, several decades of commercial-scale composting practice have convinced most discerning observers that odor generation is an inevitable result of the inevitable decomposition of organic matter – which composting advances.

Odorous compounds inherently form as raw organic materials decompose (Haug; 2004). This fact applies to both aerobic (i.e. with oxygen) and anaerobic (i.e. without oxygen) decomposition, although the latter tends to be much more objectionable. This fact also applies to both naturally occurring organic substances (e.g. leaves) and those resulting from human activities (e.g. biosolids, food residues). Thus, even a low level of odor generation can build into detectable odors when large volumes of decomposing organic materials are amassed in one location. If these odors *always* dissipate before leaving the composting site, all would be well, but that is not *always* the case.

Recognizing the reality—that the formation of odorous compounds is an unavoidable fact—the composting industry has shifted its odor control emphasis from perfecting the process to managing the facility. The goal is to reduce the impacts of odors on the community to acceptable levels. The ideal is to eliminate the impacts. The hope is to limit the impacts to some level of tolerance.

Managing odors to minimize impacts still requires knowledge of, and attention to, the composting process because the process largely determines the level and type of odors generated. However odor management also requires knowledge of, and attention to, other factors including feedstock characteristics, odor sources, odor release and meteorological and geographic conditions. These factors affect odor dispersal and travel, odor containment, treatment methods, materials handling, air handling, facility siting, predictive modeling, odor chemistry, odor measurement, community relations and politics. The conditions that lead to an off-site odor impact can be complex.

This report summarizes the current state of knowledge and practice concerning the odor impacts from composting facilities. The information has been drawn from a variety of publications and references, primarily related to composting specifically. However, literature associated with other odor-relevant fields was consulted including wastewater treatment (WWT), municipal solid waste management (MSW), agriculture and industrial processes (e.g. rendering). In order to address the complexities of odor incidents, the report examines the following questions:

- What are "odors" and what are their effects?
- How are odors detected and measured?

- What chemical compounds are responsible for odors at composting?
- What conditions lead to the formation of odorous compounds?
- What conditions and factors lead to off-site impacts (e.g. odor complaints)?
- What determines the severity of off-site impacts?

Together the answers to these questions address the broader question: what causes, conditions and factors lead to odor problems from composting facilities? The next broad question to ask is: how can these odor problems be resolved, anticipated and prevented?

What Are “Odors” and What Are Their Effects?

Before questioning what causes odors, it is helpful to understand just what constitutes an “odor.” An odor, or smell, is the sensation that our brains generate in response to certain chemicals in the air and breathed in through the nose (Dalton, 2003b). The stimuli for odors are airborne environmental chemicals – “odorants” or odorous compounds—those react with receptors in the nose and, in turn, produce the odor sensation in the brain. Examples of chemicals that commonly translate to odors at composting facilities include ammonia, hydrogen sulfide, dimetheyl sulfide, butyric acid, putrascene and terpenes. These chemicals arise in nature, as a result of the decomposition of organic substances. The resulting odors are our perceptions of them. Humans can perceive most odors even at relatively low concentrations of the chemicals, in parts per billion in many cases (Dalton, 2003b).

Perhaps because they are perceptions, odors are subjective. Humans differ in their sensitivity to the odorous compounds in the air. Where some people detect an odor to be strong, others sense it as weak or even non-existent (Schiffman, 1998). In addition, people differ in their reaction, preference and aversion to the odors that they perceived. An objectionable odor to one person can be tolerable to another. The perception of odor depends on both the characteristics and concentration of the odorant and the characteristics of the person smelling the odorant (see later section).

A person can find an odor to be pleasant or objectionable, depending on the nature of the odorants and their concentration. In composting situations, odors imply an objectionable sensation. When an unpleasant odor persists or occurs frequently, especially in an unexpected location, it is likely to create a nuisance and lead to complaints. Odor complaints are often accompanied by claims of impaired health from exposure to the odors (Schiffman et al., 2000). However, there is little evidence linking odors directly to physiological effects at the odorant concentration levels typically found outside of composting facilities (or livestock farms or waste treatment facilities) (Cain, 2006; Dalton, 2003a; Shiffman et al, 2003).

How Humans Perceive Odors—The Human Olfactory System

Human odor sensation starts when air is breathed in through the nose. Some of the air breathed in passes through the olfactory system of the nose—a serpentine pathway with protrusions, hair-like cilia, mucous membranes and chemical receptor-cells that together filter and react with numerous chemical compounds (i.e. odorants). The part of the nose containing the odor receptors is the olfactory epithelium, which is situated in the upper and back section of the nose. During normal breathing, approximately 10 percent of the air breathed in passes to the olfactory epithelium (Dalton, 2003b). Deliberate or involuntary sniffing can increase that to 20 percent (Chiumenti et al., 2005). Through a series of chemical reactions, signals travel from the odor receptors to nerves in the olfactory bulb, which translates the signals to the brain (Dalton, 2003b). How the brain processes these signals and relates the odor sensation to experiences and memory is apparently complex and not completely understood (Shiffman, 1998).

Two separate nerve systems are at work, each creating a different type of sensation in response to airborne chemicals (although the brain combines them into a single perception of the odor). The first, known as the first cranial nerve, or olfactory nerve, generates perceptions associated with the qualities of odor – flowery, fruity, putrid, etc. (Dalton, 2003b). The second system, the fifth cranial or trigeminal nerve, produces sensations of irrigation or pungency. The odor sensations from the olfactory nerve apparently do not produce a physiological response (Dalton, 2003b). However, sensations from the trigeminal system can produce responses such as a running nose, red eyes or sneezing when an irritant, like ammonia, is detected in sufficient quantity (Das, 2000; Dalton, 2003b). The chemical concentrations required to trigger irritation from the trigeminal system are typically many times (>7x) greater than the concentrations at which odors are detected (Haug, 1993; Dalton, 2003b, Wilmink and Diener, 2001).

Odors as a Nuisance

Malodors are primarily considered to be a nuisance. The term nuisance has taken on a legal meaning because of conflicts between neighboring land uses (and not necessarily on adjacent land). In general, a nuisance occurs when one person interferes with the right of other people to enjoy their own property or life (Brant and Elliott, 2004). Each state has its own statutory or judicial definition, which generally follow this general definition. McGinley et al. (2000) list the following examples:

- "Anything which is injurious to health, or indecent or offensive to the senses, or an obstruction to the free use of property, so as to interfere with the comfortable enjoyment of life or property, is a nuisance." (Minnesota)
- "…air contaminants (including odor) in quantities and duration to injure human health and welfare." (Alabama)
- "…unreasonably interfere with enjoyment of life and property." (Alaska)
- "…unreasonable interferes with the comfortable enjoyment of life or property of a substantial part of the community." (Arizona)
- "...Odor constitutes a nuisance if it unreasonably interferes with the enjoyment of life or use of property." (Connecticut)
- "…odors beyond his property…to create a public nuisance… defined includes affecting a considerable number of persons and injurious to health or interfere with the comfortable enjoyment of life and property." (Montana)

In determining whether an odor, or any other intrusion, constitutes a nuisance, courts usually apply the concept of “reasonableness” to the situation (Brant and Elliott, 2004). For instance, it may be necessary to determine if a composting operation is reasonably well-managed and took reasonable steps to prevent odor impacts. Also, it may be questioned whether the complaining neighbors are being reasonable in their demands to eliminate or reduce the odor levels. Farms, and on-farm composting, are often afforded more protection against nuisance complaints because the nature of farming (i.e. inherently odorous) and because of their historic connection to the land. Nevertheless, even farms must operate in a reasonable manner to retain that protection.

In California, the regulation of nuisance odors is more procedural and official than in most other states. All commercial composting facilities in California are required to "prepare, implement, and maintain" a site-specific Odor Impact Minimization Plan or *OIMP* (Title 14 California Code of Regulations, Chapter 3.1 §17863.4; California Integrated Waste Management Board. 2005).

The OIMP process was developed as a response to legislation that gave primary authority over odor complaints at composting facilities to the CIWMB (Health and Safety Code 41705), but required the CIWMB to develop odor regulations and procedures. The OIMP process relies on a philosophy of constant improvement, rather than prescriptive standards. California does not have numeric criteria for when an odor becomes a nuisance. Rather, a facility handling compostable organic materials is required to prepare, implement, and maintain an OIMP. The OIMP must describe design and operational procedures for minimizing odors.

The OIMP also describes meteorological conditions and a complaint response protocol. The OIMP and the facility are typically inspected monthly (although some types of facilities are inspected quarterly). The LEA determines whether or not the facility has an OIMP and is implementing the practices described in the OIMP. If the LEA finds that the facility is not implementing the procedures outlined in its OIMP, the LEA may issue a Notice and Order. If the LEA finds that the OIMP is being fully implemented, but odor impacts are still occurring, the LEA may require the operator "to take additional reasonable and feasible measures to minimize odors." A complete copy of the regulations relating to Odor Impact Minimization Plans is contained at the end of this chapter.

At best, an unpleasant odor is annoying and makes one uncomfortable. However, because people react strongly to unpleasant odors, the word "nuisance" may seem too mild of a term. Odors bring information to a person about the surrounding environment (Dalton, 2003b). Odors say whether the things before us are good or bad, safe or dangerous.

Odors provide clues about food (e.g. good to eat or spoiled), substances to avoid that might harbor disease (e.g. fecal matter) and even the presence of danger (e.g. smoke). While some of these association are subconscious, rooted in evolution, others are more deliberate. For example, Dalton (2003) explains that before microorganisms (i.e. germs) were discovered, disease and sickness were attributed to the "miasma" of the ambient air. Because odors defined the character of the air, odors were considered a cause. The association between odors and disease still persists, even though it is well known that germs cause disease, not the chemicals that generate odors.

Considering the vital information that the sense of smell provides, particularly as primordial function, it is understandable why malodors bring such a strong reaction. People continue to equate bad odors with bad things. To many people odors imply risks, hazards and danger. Ironically, people have apparently become more sensitive to and intolerant of odors, even while the risks in the environment have declined and air quality has improved. Dalton (2003) attributes this phenomenon to the fact that there is less a background odor, or odor "noise" to distract us. With little background odor, people better detect and concentrate on individual odors, and their risks. The relatively clean background environment makes even low levels of odor standout as unusual and intolerable.

Odors and Health

With the possible exception of enclosed spaces and vessels, the chemical compounds responsible for odors at a composting facility are not present in large enough concentrations to cause direct physiological harm (Dalton, 2003b; Pelossi, 2003). That is, the concentrations are below the threshold levels that cause irritation via the trigeminal system. Yet, people still claim to experience symptoms of ill health due to odors. The symptoms most often reported include nausea, eye, nose and throat irritation, headache, shortness of breath and drowsiness (Chiumenti et al., 2005; Schiffman, 1998). Without a cause-and-effect relationship, the question that follows is: Are the symptoms real (i.e. physiological) or perceived (i.e. psychological)?

The answers offered by researchers are not definitive but appear to suggest that symptoms arise from people's reaction to odors rather than a direct physiological effect. In 1998, a conference of experts, held at Duke University, examined the potential health effects of odors from livestock farms, wastewater treatment and biosolids recycling (Schiffman et al., 1998). The participants identified the following three ways in which odors might cause health symptoms:

1. A person is exposed to an odorous chemical compound at concentrations high enough to produce sensory irritations. The person associates the symptoms with the odor, although they are actually caused by the chemical odorant. As mentioned above, odorous compounds are rarely present in high enough concentrations to cause direct irritation. Therefore, this situation is not prevalent.

2. A second agent may accompany the odor, such as pathogenic bacteria. The person becomes ill from exposure to this second agent but associates the symptoms with the odor. Although this scenario cannot be easily ruled out, there is little or no evidence that suggests it occurs.

3. Odors at concentrations high enough to be detected but below the irritant threshold affect people in other ways. They change their behavior or thoughts in ways that lead them to experience the symptoms. (For example, when exposed to an odor, a person may alter their breathing by holding their breath, taking shallow breaths or breathing only through their mouths. Hence, they may become light-headed or develop a sore throat (Dalton, 2003b)). Persistent or frequent odors may increase stress, depress a person's mood or cause them to negatively change their behavior in ways that bring on physical symptoms. The conference participants concluded that more research is needed to assess and better understand the associations between these "biological and behavioral/psychosocial factors" (Schiffman, 2000).

Assuming that the third scenario is a reasonable explanation of the situation, one might say that people are making themselves sick in response to the odors. The odors themselves are not the direct cause of the reported health effects. Some odor scientists agree that there is an absence of cause and effect when it comes to health and nuisance-level odors. In an article by Pelosi (2003), William Cain of the Chemosensory Perception Laboratory at University of California, San Diego is quoted, "You can have symptoms from odors you don't like but this is not illness. Most of these are non-specific symptoms that can have any number of origins." Dr. Cain repeated this sentiment at the recent U.S.

Composting Council Conference and reiterated his view that there is “almost no” evidence to link the sensation of odors with illness (Cain, 2006).

California Odor Minimization Plan

17863.4. Odor Impact Minimization Plan [OIMP]

(a) All compostable material handling operations and facilities shall prepare, implement and maintain a site-specific odor impact minimization plan. A complete plan shall be submitted to the EA with the EA Notification or permit application.

(b) Odor impact minimization plans shall provide guidance to on-site operation personnel by describing, at a minimum, the following items. If the operator will not be implementing any of these procedures, the plan shall explain why it is not necessary.

(1) an odor monitoring protocol which describes the proximity of possible odor receptors and a method for assessing odor impacts at the locations of the possible odor receptors; and,

(2) a description of meteorological conditions effecting migration of odors and/or transport of odor-causing material off-site. Seasonal variations that effect wind velocity and direction shall also be described; and,

(3) a complaint response protocol; and,

(4) a description of design considerations and/or projected ranges of optimal operation to be employed in minimizing odor, including method and degree of aeration, moisture content of materials, feedstock characteristics, airborne emission production, process water distribution, pad and site drainage and permeability, equipment reliability, personnel training, weather event impacts, utility service interruptions, and site specific concerns; and,

(5) a description of operating procedures for minimizing odor, including aeration, moisture management, feedstock quality, drainage controls, pad maintenance, wastewater pond controls, storage practices (e.g., storage time and pile geometry), contingency plans (i.e., equipment, water, power, and personnel), biofiltration, and tarping.

(c) The odor impact minimization plan shall be revised to reflect any changes, and a copy shall be provided to the EA, within 30 days of those changes.

(d) The odor impact minimization plans shall be reviewed annually by the operator to determine if and revisions are necessary.

(e) The odor impact minimization plan shall be used by the EA to determine whether or not the operation or facility is following the procedures established by the operator. If the EA determines that the odor impact minimization plan is not being followed, the EA may issue a Notice and Order (pursuant to section 18304) to require the operator to either comply with the odor impact minimization plan or to revise it.

(f) If the odor impact minimization plan is being followed, but the odor impacts are still occurring, the EA may issue a Notice and Order (pursuant to section 18304) requiring the operator to take additional reasonable and feasible measures to minimize odors.

Authority cite: Sections 40502, 43020, 43021 and 43209.1 of the Public Resources Code.

Reference: Sections 43020, 43201 and 43209.1 of the Public Resources Code.

The California Integrated Waste Management Board regulations are posted here: http://www.ciwmb.ca.gov/Regulations/Title14/ch31.htm#article3

There's some additional background here: http://www.ciwmb.ca.gov/LEACentral/Organics/OdorIssues/

How Are Odors Characterized, Detected and Measured?

Odors are sensations—perceptions of numerous chemical compounds. Therefore, detecting, measuring, monitoring and even describing odors are not straightforward procedures. The human element cannot be completely removed from the process because odors are subjective and because they are perceived at very low odorant concentrations. Odor science has developed special terms and techniques to describe and measure the nature and strength of specific odors. (Note: more detailed discussions of odor detection and measurement is provided by St. Croix Sensory, Inc., 2005 and Brant and Elliot, 2004).

Odor Characteristics and Parameters

There are numerous ways to characterize odors. Due to the nature of odors, both qualitative and quantitative descriptors are necessary. An odor may be described and measured according its threshold concentration, pervasiveness, descriptive quality, degree of pleasant or unpleasantness and the concentration of the odor-causing chemicals present.

Concentration of Odorants

Thanks to chemical technology, it is a relatively easy matter to measure the concentrations of chemicals in air. Therefore, it is feasible to measure and monitor for odors by sampling the air and analyzing the samples in a laboratory for the presence and concentrations of selected odorous compounds. The results are expressed in terms of the concentrations of individual compounds such as parts per million (ppm) of ammonia and or parts per billion (ppb) of methyl mercaptan. These concentrations can then be compared to data that indicate the concentrations at which humans detect, recognize and/or otherwise react to the odor caused by the chemical in question (see Table 1).

Measuring the concentrations of selected individual chemicals can be indicative of the odor situation. Tracking one of more specific compounds can help identify the sources and root causes of odors and to monitor the effects of odor mitigation practices. This practice is most useful when a particular chemical or class of chemicals dominates the odor. However, relying on chemical concentrations to indicate odors has several major limitations.

First, odors are rarely the result of a single odorant but a combination of chemicals each lending their character to the resulting overall odor. The combined effect may be greater than the sum of the individual effects. Measuring the concentrations of a single compound cannot truly represent either the quality or strength of the odor. Second, odors are detectable to humans when the odorants are present a very low concentrations. Conventional analytical techniques may not be practical or accurate at these low concentrations. Therefore, in most cases, the human nose remains the best tool for detecting and measuring odors.

“Odor” Concentration—Dilutions to Threshold

Given the limitations of measuring individual compounds, odor science has developed a method for defining the concentration of an odor *in its entirety*. This odor concentration is determined by a panel of human subjects that smell samples of the odor at various levels of dilution with fresh air (see description in following section). The concentration is expressed in terms of the number of dilutions required for the panel members to no longer detect the odor. This value is called either the dilutions-to-threshold (D/T), or effective dilutions (ED). The two terms are equivalent. Usually, the concentration is taken to be the point at which 50% the panel no longer detect the odor and it is written as D/T_{50} or ED_{50}. A few other terms and symbols are for odor concentration but they are less popular and essentially the same as D/T (Haug, 1993).

The value of D/T reflects the strength of an odor as perceived by the odor panel. A large D/T value means that the odor is strong because it requires many dilutions with fresh air to disappear. For example, at D/T_{50} of 10 means that the odor sample was diluted with a volume of fresh air 9 times the volume of the sample before half the panel members could not detect the odor. An odor with a D/T value of 5 is not as strong because it disappears with fewer dilutions.

Threshold Concentrations

Threshold concentrations refer to the concentrations that the odor or odorant results in a reaction from humans. For example, a *detection* threshold is the minimum concentration at which humans detect the odor. The *recognition* threshold is the minimum concentration at which humans can recognize or identify the odor. The recognition threshold is typically 2 to 10 times higher than the detection threshold (Brant and Elliot, 2004). Threshold concentrations can also be established for points of annoyance, tolerance and irritation, which are higher than the recognition threshold. Again, because humans vary in their sensitivities to odors, threshold concentrations are set at the point where some percentage of the populations considers the odor just detectable or recognizable. Usually the percentage is 50% and it is determined by studies with human odor panels.

Threshold concentrations can be established for overall odors and expressed as in D/T50. Also, threshold concentrations can apply to individual odorants using conventional units of concentration like ppm. Table 1 lists detection and recognition threshold concentrations for selected odor-causing compounds (see following section on “Odor Index”.

Odor “Potential”—Odor Index

The potential of a particular chemical to cause an odor problem depends on several of its odor “characteristics.” Threshold concentrations reflect the amount of the odorant that is required for people to perceive the chemical’s odor at various reaction levels, such as detection, recognition, annoyance, irritation. Whether or not the reaction is positive, neutral or negative is determined by odor characteristics that include the chemical’s odor intensity, hedonic tone, quality and pervasiveness (see previous section).

However, before an odorant can be perceived as an odor, it must first volatilize. Therefore, an important characteristic is the chemical’s vapor pressure, which indicates the chemical’s tendency to volatilize. Vapor pressure can be considered the pressure required to prevent the chemical from changing phase from a liquid to a gas. When the ambient pressure equals the vapor pressure of a chemical, the chemical starts to boil. Thus, chemicals with a low vapor pressure vaporize easily. Another way to express the tendency to vaporize is by the chemical’s boiling point (i.e. temperature). Chemicals with a low boiling temperature readily vaporize.

Haug (1993) and Das (2000) each discuss the concept of “odor index” (OI). Odor index is a measure that considers both the tendency of the odorant to vaporize and its ability to be perceived. It is a dimensionless parameter defined as the ratio of the vapor pressure to the recognition threshold concentration as follows:

$$\text{Odor index} = \text{OI} = \frac{\text{Vapor Pressure (ppm)}}{\text{Odor regomition threshold (100\%)(ppm)}}$$

When a compound vaporizes easily and is recognizable at low concentrations, it has a high OI value. Thus, compounds with higher OI values are more likely to create odors, assuming that they also have objectionable odor qualities or unpleasant hedonic tone levels. Table 1 lists the OI and other odor characteristics for selected odor compounds.

Odor Units (ou)

The strength of an odor is sometimes quantified in terms of “odor units” (ou). An odor unit is conceptually similar to D/T, although it is not well explained in the literature and can be confusing. The odor unit value essentially refers to the number of dilutions (of fresh air) required to reduce the odor to its detection threshold (Chiumenti et al., 2005). Thus, air with a large odor unit value of has a strong odor. An odor unit is a dimensionless quantity but is written as “ou,” D/T or ED (Haug, 2003).

Table 1: Threshold odor concentrations, odor index and boiling point for selected odorants

Odorant Category Chemical Compound	Detection Threshold (ppmv)[1]	Recognition Threshold (ppmv)[1]	Boiling Point Temperature (ºC)[2]	Odor Index
Acetic acid	0.008	0.2	63 @ 100d mm Hg	15,000
Ammonia	0.370	47	-33	167,300
Butyl mercaptan	0.0005		65	43,340,000
Butyric acid			61 @ 10 mm Hg	50,000

Diethyl sulfide	0.0008	0.005	88	14,400,000
Dimethyl amine	0.047	0.047		
Dimethyl sulfide	0.001	0.0056		
Ethylamine	0.026	0.83	17	1,445,000
Ethyl Mercapton	0.0005		65	43,340,000
Hydrogen sulfide	0.00047	0.0047	62	17,000,000
Methyl mercaptan	0.0011	0.0021	8	53,300,000
Proprionic acid			66 @ 40 mm Hg	112,300
Skatole	0.0012	0.47	95 @ 1 mm Hg	30,000
α-Pinene	0.011		37 @ 10 mm Hg	469,000
Butanone			80	3,800

1. ppmv = parts per million by volume
2. Unless otherwise noted (in parenthesis), the boiling point temperature is for a vapor pressure of 760 mm Hg (equivalent of standard atmospheric pressure)

Source: adapted from Haug, 1993)

Odor Intensity and Pervasiveness

Odor intensity is the perceived strength or pungency of an odor (Brant and Elliott, 2004). It is an important factor in determining the tolerance that humans have for an odor (Haug, 2003). Intensity is primarily a qualitative characteristic but it can be expressed in quantitative terms.

Odor intensity is evaluated by comparing the intensity of a sample odor with the intensity of a standard odorant at various concentrations. The most common reference odorant used in the U.S. is 1-butanol, following ASTM standard E544 (Das, 2000; Haug, 1993). The intensity is reported in terms of the corresponding butanol concentration (e.g. ppm), or with a scale number that coincides with the butanol concentration range. Brandt and Elliott (2004) describe a second method for gauging odor intensity in which human subjects simply rate the intensity of an odor sample on a scale of 0 to 6. An overpowering odor would be rated 6 and no odor would be 0.

Odor intensity and concentration both indicate the strength of an odor. They are related but different qualities. Quantitatively, intensity (I) and concentrated (C) are related by Steven's Psycophysical Law as follows (Das, 2000; Haug, 1993):

$$I = k\ C^n$$

The equation holds for either an overall odor or an individual odorant. For an overall odor, the threshold concentration would be used, expressed in D/Ts. For an odorant, the actual concentration applies. The constants k and n vary with the particular odor or odorant.

The constant n indicates how easily the odor intensity decreases when the air is diluted—that is, the concentration decreases. The value of n ranges from 0.2 to 0.8 for most compounds (Das, 2000). A low n value means that the intensity changes little as the air is diluted. The odor is said to be "pervasive." When n is large, diluting air readily reduces the intensity and the odor is non-pervasive. For example, ammonia and aldehydes have high values of n—they are easily diluted. Hydrogen sulfide and amines are examples of odor-causing compounds with low n values—their odors disappear slowly as they are diluted (Haug, 1993).

Odor Quality or Character

Odors have a quality that can only be identified descriptively by relating the to other odors that are generally familiar or widely recognized. The odor *quality* is what a person would say "an odor smells like" (Brant and Elliot, 2001). Lists of standard descriptors exist that can be used by one person to convey the quality of an odor to another person (Table 2). More than one descriptor can be used and the presence of one or more type of "smell" can be weighted.

Hedonic Tone

The *hedonic* tone is a rating of the pleasantness or unpleasantness of an odor. It is a subjective measure but it can be averaged for a group of individuals evaluating an odor. Hedonic tone can be rated on a scale from –10 for very unpleasant to +10 for pleasant (Chiumenti et al. 2005). Ratings scales can be "standardized" by relating the scale to reference odorants, such as isovaleric acid, as a model for a very unpleasant odor, and vanillin for a very pleasant odor (Haug, 1993). Hedonic tone is not an independent quality of a compound or odor. It depends on the odor intensity, concentration, duration and frequency of exposure, as well as the perceptions and associations of the individual.

Table 2: Examples of standard descriptors for odor quality

Odor Character Category							
Chemical	**Medicinal**	**Floral**	**Fruity**	**Vegetable**	**Earthy**	**Offensive**	**Fishy**
Coal	Alcohol	Almond	Apple	Celery	Ashes	Blood	Amine
Creosote	Ammonia	Cinnamon	Cherry	Corn	Burnt Wood	Burnt	Dead Fish
Diesel	Anesthetic	Coconut	Citrus	Cucumber	Chalk-like	Burnt Rubber	Perm Solution
Gasoline	Camphore	Eucalptus	Cloves	Dill	Coffee	Decay	
Grease	Chlorinous	Fragrant	Grapes	Garlic	Grain Silage	Fecal	
Paint	Disinfectant	Herbal	Lemons	Green Pepper	Grassy	Garbage	
Plastic	Menthol	Lavender	Maple	Nutty	Mold	Landfill Leachate	
Resins	Soapy	Licorce	Melon	Potato	Mushroom	Manure	
Rubber	Vinegar	Marigolds	Minty	Tomato	Musky	Mercaptane	
Solvent		Perfumy	Orange	Onion	Musty	Putrid	
Sulfur		Rose-like	Strawberry		Peat-lie	Rancid	
Varnish		Spicy	Sweet		Pine	Raw Meat	
Car Exhaust					Mouse-like	Urine	
Burnt Plastic						Vomit	
Foundry							
Turpentine							

Source: adapted from St. Croix Sensory, 2005.

Measuring Odors

Odors are measured for a variety of reasons—for research on process management or human exposure, to troubleshoot the process and improve methods, to gather data for odor models, for regulatory compliance and for legal evidence. In these instances, the measurements must be reasonably reliable quantifiable and/or qualified in a generally accepted manner. Standard procedures and methods of sampling and measurement are involved.

Practices tend to be less rigorous when odors are measured in the field for monitoring purposes. Odor monitoring is conducted to anticipate and prevent odor problems, improve process management, verify a complaint and/or spot check for regulatory compliance. Monitoring is, or should be, a regular activity so cost is a factor. Expensive procedures for sampling and analyzing odors or odor components are not often used for field measurements. Instead, human noses usually make on-site evaluations, increasingly with the aid of devices that gather and handle odor samples in the field.

In any case, there are two approaches to measuring odors – (1) observe and record the odor sensation or reactions that humans have to odors or odorous compounds; and (2) capture and measure the chemical compounds stimulating the odors. The human-based approach, known as olfactometry, is more common (Brant and Elliott, 2004). However, both approaches are used in science and practice to determine the presence, quantities and qualities of odors. Both methods require accurate sampling of the odorous air.

Sampling

Sampling is a critical element of analytical and olfactometry measurements (see following sections). Odors are usually sampled by collecting a proportional volume of air at or near the odor source. The rate at which the sample volume is collected can indicate the rate of emissions. Where odors quality is of chief importance, samples of odors also can be gathered by placing an odor-adsorbing medium, like a fabric swatch, at the source for a period of time (Brant and Elliott, 2004).

In the field, air samples are collected using a collection orifice or tube placed within the air emissions of the odor source. Air is drawn into the collection tube by either a hand operated pump (e.g. flexible bulb or piston) or a small battery-powered vacuum pump (Wilmink and Diener, 2001). The volume of air sampled must be known and is determined by the number of hand pumps or time that the vacuum pump runs. The sample air is gathered in a flexible bag that will not react with the target chemicals, commonly made of tedlar. The sample is than promptly taken to the laboratory for chemical analysis. In laboratory situations, or in applications that include real time monitoring, air samples are typically drawn from sample ports either manually or automatically, and transported to the lab for analysis.

Odors emitted from buildings and stacks are sampled from the exhaust vents, usually by taking multiple samples at predetermined points to get an accurate representation of the average airflow. Field sampling of area sources, like compost piles and biofilters, requires a hood that covers the sample area. Multiple sample areas may be necessary when the airflow is not uniform.

Olfactometry—Odor Measurement by Humans

The human nose is better at detecting and distinguishing odors than any analytical instrument currently available. Therefore, using the odor sensitivities of people is the most reliable and most accepted way to measure odors. This approach is called olfactometry.

At the laboratory level, olfactometry employs a panel of people, usually with some training, to sniff odor samples and then rate, describe and/or react to them. Because individuals sense and perceive odors differently, odor panels contain several members, preferably 5 to 10 (Haug, 1993). Their collective response is expressed statistically. For example, odor thresholds are usually defined by the point at which 50% of the panel no longer detects the odor (e.g. D/T_{50}).

Standard techniques are used to prepare the odor samples and present them to the panel and to register the responses of the panel members. A number of standard methodologies exist for olfactometry, including at least two ASTM standards (Haug, 1993).

The general procedure involves taking a sample of the odor source, as described above, and transporting the sample to the odor panel lab. The odor sample is then presented to the panel members, often at various levels of dilution. For example, an odor sample is progressively diluted at various levels and presented to panel members in order to determine a detection of recognition threshold (i.e. D/T). In nearly all cases, the nature of the sample is unknown to the panel member.

Odor panelists may also be exposed to undiluted samples for rating odor quality, intensity of hedonic tone. Some applications also may include control samples that have no odors or odorants. In some cases, panel members are presented standard comparison samples with known odorants at known concentrations. Olfactometry makes use of air handling devices that easily control the sample dilution level and/or airflow rate to the panel. Some devices make it possible to conduct olfactometry measurements in the field. However, the background odor “noise” and adaptation of the human subjects to the ambient odors can compromise the results. These devices are more often used for odor monitoring purposes (see following section).

Several portable devices have been developed for olfactory measurements of odors in the field, such as at the boundaries of the composting site. Generally, these *field olfactometers* collect a sample of air and then guide it to the user’s nose, which is isolated from the surrounding ambient air by a mask or cup covering the nose. Two commercial field olfactometers have received particular attention in the composting literature—the “scentometer,” manufactured by BernebeySutcliffe; and the Nasal Ranger, available from St. Croix Sensory, Inc. (McGinley and McGinley, 2005; Myers, 2004; Das, 2000)

These devices have filters to provide fresh air to dilute the odorous air reaching the human user. They also have valves to adjust the mixture of fresh and odorous air. In addition to providing for more user-friendly operation, field olfactometers have developed to more accurately control the dilution rate. Thus, field measures can estimate threshold concentrations in D/Ts.

Analytical Measurements

Analytical measurements quantify the amount of concentration of a specific chemical using various chemical, electrical or physical techniques. For odor measurement, the analytical approach is practical when one or a few specific and identifiable compounds dominate the odor. Analytical measurements also can be useful when measuring changes in odor-relevant situations. For example, one can use analytical methods to track hydrogen sulfide concentrations in response to some odor mitigating practice, like adding a porous amendment to improve aeration. Even if hydrogen sulfide is not the offending odor, its presence and concentration may be indicative of odors.

Numerous analytical techniques and instruments are commonly used. The target odor chemical and the range of concentrations that need to be measured typically determine what techniques are feasible. The combined use of gas chromatographs and mass spectrometers is especially versatile, accurate and popular.

Detection Tubes

Detection tubes serve as both sampling and analytical devices. They are convenient for evaluations of odors in the field. One of the more common types of detection tube is called a Dragger tube, which is often used to measure ammonia concentrations on the spot. The detection tube contains a chemical that reacts with the target odorant compound and changes color, expands or changes in some fashion in proportion to the amount of odorant present. The scale on the tube is calibrated to display the concentration of the odorant.

A fixed volume of air (e.g. set number of hand pumps) must be drawn into the tube for the calibration to be accurate. Detection tubes are only moderately accurate in analyzing concentrations (Wilmink and Diener, 2001). However, they are convenient and inexpensive devices for field use in monitoring changes and determining if a particular compound is present. A different type of detection tube is required for different target compounds. Although detection tubes are available for a large number of compounds, many are not sensitive or accurate enough at the low concentrations at which odors typically arise.

Laboratory Analytical Methods

Samples taken to laboratories are analyzed via a variety of analytical techniques that yield a measure of the chemical concentrations. The technique used depends on its suitability to the target chemicals, accuracy required, capabilities of the laboratory and cost. Commonly used techniques for analyzing odorous compounds include the following (Brant and Elliot, 2004; Wilmink and Diener, 2001):

- Wet chemistry: Appropriate for analyzing target compounds that are soluble in water. Ion specific electrodes (ISE) are commonly used.
- Electrochemical sensors: An electrode that reacts with a specific gas, causing an electrical signal that can be translated to a concentration. The electrodes are fast, and sensitive to low concentrations but can suffer from interference from non-target gases.
- Semiconductor sensors: Metal oxide semi-conductors increase in electrical conductivity in the presence of reducing gases. These sensors can be used to detect certain categories of gases (e.g. solvents) at low concentrations but not specific chemicals. They do not appear to be broadly applicable to the chemicals that typically cause composting odors.
- Photoionization detector: Uses UV light to ionize and then measure the concentration of volatile organic compounds.
- Gas chromatography (GC) and mass spectrometry (MS): These common laboratory techniques separate and analyze individual volatile or gaseous chemical compounds

from a mixed air stream. Used together, a GC/MS system can analyze a wide variety of organic compounds with accuracy.

Electronic Nose

Brant and Elliott (2004) put the “electronic nose” in the category of “emerging odor management strategies.” An electronic nose, or artificial nose, is an instrument that includes a system for sampling air (or gases generally), multiple gas-detecting sensors and a computer with an artificial intelligence program (e.g. neural networks). Each sensor detects and quantifies a different specific chemical gas and sends a corresponding electronic signal to the computer.

The computer program recognizes the pattern of signals generated by the array of sensors. An electronic nose is intended to mimic the human olfactory system. Like a human nose, the sensors detect a combination of gaseous chemical compounds, at varying concentrations, and electronically inform the ”brain,” in this case a computer, which recognizes and describes the odor (Stetter and Penrose, 2001).

According to the *Whatis.com web site (2003)* , electronic noses have been used for years, primarily for quality control in the food and beverage industry. Until recently, the large size and expense of the instruments have hampered widespread use. Electronic noses have been shrinking in size and expense due to research and development efforts. Brant and Elliott suggest that electronic noses must be “trained” to perceive odors like humans based on the perceptions of human odor panels -- a time consuming process. Also, they note that the capabilities of the gas sensors also limit the applications to concentrated odor sources (e.g. point sources).

Electronic noses appear to be improving and might soon become practical for automated odor detection. A good technical article describing electronic noses (Stetter and Penrose , 2001) can be found on the Electrochemical Encyclopedia web site at http://electrochem.cwru.edu/ed/encycl/art-n01-nose.htm .

What Chemical Compounds Are Responsible for Odors At Composting Facilities?

The odor associated with composting is not the result of a single “smell.” Organic materials inherently generate a large number and variety of volatile chemical compounds that humans can sense as odors—good and bad. These compounds can coexist and interact with one another to produce a diverse menu of aromas. A compound’s volatility—that is, its conversion to a gaseous phase and subsequent migration into the air—is what causes it to be sensed by human noses (and “noses” of other animals). Volatility is necessary for chemicals to be odorous.

As an organic material decomposes, the mix of volatile compounds changes, and so does the characteristic odor. A smell may “appear” where one was not apparent before, or the reverse may be true—a smell may disappear. In any case, the quality of the odor changes as organic materials pass through different stages of decomposition. The quality also changes with the variation in conditions responsible for the formation and movement of specific volatile compounds. During composting, many volatile chemicals are formed, destroyed and/or emitted due to the innumerable combinations of raw feedstocks and the diverse and ever changing process conditions. They can coexist and interact with one another to produce a diverse menu of aromas.

Before considering the specific compounds associated with composting odors, it is important to recognize the following “truisms:”

- Usually, the characteristic smell of a given material is a result of a mix of several volatile compounds, each related to the chemical composition of that material. A particular volatile chemical can dominate the mix and produces the characteristic odor.
- Most odorous compounds are transient. After forming, or being liberated, they decompose, immobilize, change phase and/or disperse relatively quickly, depending on the environmental conditions (e.g. oxygen, temperature—see following section).
- The concentration of a particular compound determines whether or not its odor is detected, recognized and considered objectionable. Odorous substances that are generally considered pleasing can become offensive at high concentrations (e.g. perfume, pine oil). Whether people find an odor good or bad, pleasant or unpleasant, is a quality known as “hedonic tone.” The hedonic tone says nothing about the character of the odor (e.g. pungent, septic, fishy), just how good or bad it is perceived to be.
- The concentration at which a compound is detected by people, its detection “threshold,” varies greatly among volatile compounds. Some compounds can be detected at extremely low concentrations while others require high concentrations.
- The character and strength of odors are highly subjective—sensed and judged differently by different people.

- An individual’s sensitivity to an odor, and his/her reaction to it is greatly influenced by personal experience, gender, psychology and societal factors (Dalton, 2000a, 2000b).

Many compounds formed during composting are “odorous,” that is considered offensive by at least some humans. Several individual compounds stand out as odorous, such as ammonia and hydrogen sulfide. However, because of the large number of chemical species involved, odorous compounds are frequently identified by categories of similar chemicals. The primary categories identified with organic materials are mercaptans, organic sulfides, ammonia, amines, indoles, volatile fatty acids (VFAs), terpenes, alcohols, ketones and aldehydes, (Haug, 1993; Miller, 1993; Epstein, 1997; Goldstein, 2002). The first two in this list, along with hydrogen sulfide are compounds that contain sulfur. Amines, indoles and ammonia are nitrogen-based compounds. Volatile fatty acids (VFAs) are most closely associated with carbohydrates and lipids (i.e. fats and oils). The remaining groups are common organic compounds with volatile members.

Table 3 lists compounds and groups that are commonly associated with odors at composting facilities. The characteristics of individual compounds and groups are described below.

Table 3: Common odorous compounds released during handling and decomposition of organic materials

Compound Name	Odor Descriptors	Chemical Formula	Molecular Mass
Volatile Sulfur Compounds			
Hydrogen sulfide	Rotten egg	H_2S	34
Methyl-mercaptan	Pungent, rotten cabbage, skunk, garlic	CH_3SH	48
Ethyl-mercaptan	Rotten cabbage, leek-like	C_2H_5SH	62
Carbon disulfide	Disagreeably sweet, rotten pumpkin	CS_2	76
Dimethyl sulfide	Sulfurous, rotten cabbage,	$(CH_3)_2S$	62
Dimethyl disulfide	Putrid, sulfurous	$(CH_3)_2S_2$	94
Volatile Nitrogen Compounds			
Ammonia	Pungent, sharp, irritating	NH_3	17
Putrescine	Putrid, nauseating	$NH_2(CH_2)_4NH_2$	88
Cadaverine	Putrid, decaying flesh	$NH_2(CH_2)_5NH_2$	102
Methylamine	Putrid, fishy, rotten fish	CH_3NH_2	31
Dimethylamine	Fishy, rotten fish	$(CH_3)_2NH$	45
Trimethylamine	Fishy, pungent	$(CH_3)_3N$	459
Ethylamine	Ammonia-like, irritating	$C_2H_5NH_2$	45
Indole	Fecal, nauseating	$C_6H_4(CH_2)_3NH$	117
Skatole	Fecal, nauseating	C_9H_9N	131
Compound Name	**Odor Descriptors**	**Chemical Formula**	**Molecular Mass**
Volatile Fatty Acids (VFAs)			
Formic acid	Biting, pungent	HCOOH	46
Acetic acid	Vinegar-like, pungent	CH_3COOH	60
Propionic acid	Rancid, pungent	C_2H_5COOH	74
Butyric acid	Rancid butter, body odor	C_3H_7COOH	88
Valeric acid	Unpleasant, sweat	C_4H_9COOH	102

Compound Name	Odor Descriptors	Chemical Formula	Molecular Mass
Iso-valeric acid	Rancid cheeses	$(CH_3)_2C_2H_3COOH$	102
Caproic acid	Pungent	$C_5H_{11}COOH$	116
Capric acid	Unpleasant, offensive	$C_9H_{19}COOH$	172
Terpenes			
α-Pinene	Sharp, terpentine	--	--
Limonene	Sharp, lemony	--	--
Ketones and Aldehydes			
Phenol	Medicinal	C_6H_5OH	1094
Acetone	Pungent, solvent	CH_3COCH_3	58
Methyl ethyl ketone (Butanone)	Sweet, solvent	$CH_3COCH_2CH_3$	72
Formaldehyde	Acrid, medicinal	H_2CO	30
Acetaldehyde	Green, sweet, fruity	CH_3CHO	44

Compiled from: Brant and Elliott, 2004; Chiumenti et al., 2005; Williams and Miller, 1993; Wilmink and Diener, 2001; and Epstein, 1997

Sulfur Compounds

The element sulfur (S) is a common to several of the more objectionable, potent and recognizable odorous compounds associated with organic matter decomposition. Sulfur is a relatively abundant element in many composting feedstocks including food residuals, produce, paper, gypsum, manure and biosolids (Miller,1993). It is a component of the amino acids cystine and methionine, which serve as precursors for volatile sulfur compounds, as organic matter decomposes (Miller,1993). Many volatile sulfur compounds form under both aerobic and anaerobic conditions, although the latter produces and/or accumulates more (Walker and Gossett, 1999, Haug, 1993). Sulfur compounds principally identified as odorous include hydrogen sulfide, mercaptans and organic sulfides (e.g. dimethyl disulfide).

Hydrogen sulfide

Hydrogen sulfide (H_2S) is a reduced and inorganic form of sulfur that produces the familiar rotten egg smell. While it can form at low oxygen concentrations (anoxic), it primarily is an anaerobic product. The presence of hydrogen sulfide is an indicator of anaerobic decomposition of organic matter (Nobel et al., 2001). Although hydrogen sulfide produces an offensive odor, and it can be detected at very low concentrations, it does not appear to be a major source of odors at composting facilities. Few field-based studies have implicated this compound as a primary offending odor. This result may stem from the tendency of hydrogen sulfide to dissipate and/or oxidize quickly in the environment (Walker and Gossett, 1999). Also, hydrogen sulfide is not volatile at pH levels above 8 (Das, 2000). However, hydrogen sulfide has been reported is a prominent odor in certain circumstances such as where large quantities of gypsum (e.g. dry wall) are used for mushroom substrate composting (Miller, 1993). Hydrogen sulfide is heavier than air and can accumulate in confined environments, raising the possibility of asphyxiation.

Mercaptan (thiols)

Mercaptans, also termed *thiols* by chemists, are another group of volatile organic sulfur compounds that are characterized by a strong odor and detectable at low concentrations (Haug, 1993). Naturally occurring mercaptans are responsible for the odors that skunks emit and the aromas of garlic and onions. Two specific compounds associated with composting are ethyl mercaptan, also known as ethanethiol, and methyl mercaptan, or methanethiol. Of the two, methyl mercaptan is more often identified as a composting odor. Its characteristic odors is described as rotten cabbage or sulfide-like, (Wilmink and Diener, 2001; Miller, 1993). It is used in low concentrations to impart an odor to natural gas. In decomposing organic matter, mercaptans result from the early steps of protein degradation (Miller, 1993). They can form aerobically but form or accumulate to a greater extent under anaerobic conditions (Epstein, 1997, E & A Consultants, 1993). Mercaptans have been identified as contributors to composting odors from several feedstocks, including food, paper processing residuals, biosolids and swine manure (Fraser and Lau, 2000, Walker and Gossett, 1999, Kuroda et al., 1996, E & A Consultants, 1993, Haug, 1993).

Organic Sulfides

Volatile organic sulfur compounds associated with odors include dimethyl disulfide (DMDS), dimethyl sulfide (DMS) and carbon disulfide (CS). These sulfur compounds have a strong offensive odor and likewise are detectable at low concentrations. They are often cited as the dominant sources of odors where manure, and especially biosolids, are handled. Organic sulfides are generated from the successive degradation of sulfur-containing proteins and “intermediate” by-products (e.g. methyl mercaptons). CS and DMDS are reported to form non-biologically (i.e. strictly chemical reactions) as well as biologically (Miller, 1993; Derikx et al., 1991). While these sulfur compounds can form whether oxygen is present or not, they persist under anaerobic conditions. They further decompose to innocuous compounds under aerobic conditions. Thus, when degradation is predominantly anaerobic, the concentrations present (and emitted) are much higher, by a factor of 10 or greater (Walker and Gossett, 1999). Of these organic sulfides, DMDS appears to be the major odor source at biosilids composting facilities (Goldstein, 2002, Epstein, 1997, Hentz et al., 1996, Derix et al, 1991). However, DMDS and, to a lesser degree, the other organic sulfides appear to be primary contributors to odors with any feedstock that contains moderate to high sulfur contents, including food, manure and paper sludge (Miller, 1993; E & A Consultants, 1993; Noble et al, 2001; Defoer et al., 2002; Derix et al, 1991; Kuroda et al., 1996; Walker and Gossett, 1999).

Nitrogen Compounds

The decomposition of proteins and other organic substances generates a number of nitrogen-based compounds that are volatile and odorous. Ammonia is by the far the most prominent and important or these in terms of nitrogen (N) loss (Kuroda et al., 1996; Miller, 1993). Because of their offensive odors, two groups of organic nitrogen compounds are also notable -- amines and indoles. Whenever nitrogen is abundant, and especially where carbon to nitrogen ratios (C:N) are low (< 25:1), odorous nitrogen compounds are likely to be emitted. Greater quantities are generated as the proportion of available nitrogen increases. These nitrogen compounds develop inherently as proteins decompose. Under aerobic conditions they continue to decompose and disappear relatively quickly, with the exception of ammonia.

Ammonia

The pungent smell of ammonia is familiar to most people. Ammonia and its pungent odor are present at many composting facilities, at least at those facilities that handle feedstock mixtures that have a high nitrogen content (e.g. with healthy proportions of manure, biosolids, fish, grass). In fact, ammonia is appreciably generated and emitted wherever high-nitrogen wastes are produced, stored or handled. Chemically, ammonia is the nitrogen analog to hydrogen sulfide. Ammonia (NH_3) is an inorganic volatile and reduced form of nitrogen that results from the degradation of protein, urea and nearly any degradable compound with nitrogen. It forms under both aerobic and anaerobic conditions. Ammonia is generated in large concentrations and amounts whenever the C:N ratio of the combined material is relatively low (< approximately 20:1) and the pH is elevated. With increasing pH, the water-soluble ammonium ion (NH_4) shifts to the volatile and odorous gaseous form of ammonia (NH_3).

Because of its strong smell and presence, ammonia is an odor concern for composting facilities, but usually within the facility's bounds. It is rarely the cause of odor complaints that occur beyond the facility. There are several reasons for this situation. First, ammonia has a high odor threshold (i.e. it takes relatively high concentrations to be detected). The character of the odor is not particular offensive to most individuals. Many people are familiar with the smell of ammonia and do find it suspicious. Perhaps most importantly, like H_2S, ammonia tends to dissipate rapidly after it is emitted (Haug, 1993). In short, because of its ubiquitous nature, ammonia remains an important odor compound but, in most cases, primarily near the point where materials are stored and handled. However, ammonia can be a serious problem with feedstocks that carry very high nitrogen contents such as poultry manure and fish waste, especially where large amounts of these materials are concentrated.

Amines

Amines are foul smelling volatile organic nitrogen compounds, that result from the decomposition of proteins and amino acids (Haug, 1993). In chemical structure, some amines are similar to organic sulfur compounds. The odor character of amines is suggested by the common names of two particular compounds – putresine and cadaverine. Both of these putrid-smelling compounds occur in decaying animal tissue. Some other amines that may contribute to odors include methylamine, ethylamine and trimethylamine. These amines tend to impart an odor that is often described as fishy and/or ammonia-like. While amines are often cited as potential sources of odor, none of the field studies reviewed specifically identified amines as a major component of odors at composting sites. Nevertheless, one would intuitively expect them to be present and to affect the odor quality at facilities that handle highly degradable nitrogen-rich feedstocks like fish waste, animal mortalities, poultry manure, grass and biosolids.

Indoles

Indoles are a group of *heterocyclic* nitrogen compounds (which means that they have a molecular ring structure with a nitrogen atom in place of a carbon). Two compounds in this group, indole and skatole, are known for their feces-like odor. Skatole is often noted for its descriptive name. These compounds are produced by bacterial decomposition of the amino acid tryotophan and other proteins (answers.com 2005; Sawyer and McCartney, 1978). Bacteria in animal intestines produce indole and skatole, which produce the offensive smell of fecal matter. However, plants also produce indoles (e.g. the pigment in indigo). Ironically, at low concentrations these compounds can have a pleasant odor. They are the source of scent in some perfumes and flowers (e.g. orange blossoms) (answers.com, 2005). Indoles and skatole have not been identified as major odor sources at composting facilities. However, they undoubtedly contribute a negative character to the general odor quality where manure and biosolids are handled and processed. They would be most apparent when handling these feedstocks and at the early stages of composting. These compounds do not persist under aerobic conditions (Wilmink and Diener, 2001)

Volatile Fatty Acids (VFA)

Volatile fatty acids (VFA) are also referred to by the more general term volatile organic acids. They result from the decomposition of long chained organic acids that are common components of carbohydrates, fats and oils. As these compounds (and long chained acids) decompose, they split off low molecular weight VFAs. If oxygen is present, VFAs further decompose into carbon dioxide and water. If oxygen is not present, they accumulate and readily volatilize, potentially leading to odors. Depending on the parent compounds, numerous VFAs can develop during decomposition, each with a characteristic odor. In large enough concentrations, the odors are offensive. The most recognizable VFA is acetic acid or vinegar. Formic, propionic, valeric and butyric acids are other examples with disagreeable odors that range in quality from rancid to putrid (see Table 1). A VFA with a higher molecular weights tends to have a more intense odor than a VFA with a lower molecular weight (Goldstein, 2002).

Odors from VFAs are possible with almost any organic material, especially when anaerobic conditions prevail. VFAs are more likely to be the primary contributor to odors when nitrogen and sulfur are not abundant, and thus sulfides and amines do not dominate the overall odor. Green wastes, food and mixed MSW composting facilities can be troubled by odors from VFAs. For example, the characteristic smell of “garbage” is attributed to butyric acid. However, VFAs can be a significant contributor to odors even in feedstocks with abundant nitrogen and S, like swine manure (Kephart and Mikesell, 2000).

Terpenes

Terpenes are aromatic compounds that are naturally produced by various plants (see Table 1). They contribute to the fragrance of many plants including lemons, geraniums, rose, mint, pine and eucalyptus (Haug, 1993). As plant materials are amassed, processed (e.g. chipped and shredded) and handled, these aromatic compounds are liberated from the plant cells. If they remain within the confines of the composting pile or vessel, they decompose. However, when exposed to the air, or drawn out by air currents, these readily volatile compounds are released.

By themselves, at low to moderate concentrations, the smell of terpenes is not offensive to most people. However, at high concentrations, terpenes may present an odor that is annoying, if not offensive. Also, when mixed with the soup of other odors of decomposing materials, they may add to the intensity of an overall disagreeable smell. At composting facilities, terpenes appear to be prominent where woody materials are composted, such as brush and tree branches at green waste facilities, sawdust bedding in manure, and wood chip bulking agents used in composting biosolids (Epstein, 1997)

Other Volatile Organic Compounds

Odors can emanate from several other categories of common volatile organic compounds including ketones, aldehydes and alcohols, among others. These groups encompass very common organic substances that form and disappear as nearly all types of organic compounds react with one another. For example, aldehydes and ketones are produced from the oxidation of different types of alcohols and further oxidize to form organic acids. Alcohols result from the oxidation of hydrocarbons.

These types of compounds occur naturally as complex organic substances degrade. In aerobic environments they tend to be short lived. Many compounds within these groups have an odor associated with them. Whether or not the odors from alcohols are unpleasant depends on the concentrations, intensity, human sensitivity to these compounds and the presence of other odorous substances. In general, they are rarely a primary component of malodors at a composting site but can contribute negatively to overall odor character. In certain situations, or with specific materials, an alcohol, ketone or aldehyde may produce a detectable and dominant odor.

Alcohols

Alcohols occur readily as organic molecules decompose. They can form aerobically or anaerobically but accumulate under anaerobic conditions (e.g. fermentation of wine). In composting, they would be detected if anaerobic conditions persist or if other conditions interfere with their continued aerobic decomposition. Such conditions occasionally occur when carbohydrates are abundant and their subsequent decomposition leads to an accumulation in organic acids.

The organic acids can depress the pH low enough to retard further decomposition of the alcohols that form. With time (and oxygen), the pH increases and alcohols eventually decompose but in the meantime, the material can emit the sour smell of alcohols. This situation is a typical of feedstocks that are rich in easily degradable carbohydrates (e.g. potato culls, some food wastes). It can be prevented by adding a liming or buffering agent to counteract the pH drop (Woods End Research Laboratories, 1990). When odors result from alcohols, the situation is relatively short-lived. Humans sensitivity to alcohols is moderate to low (Goldstein, 2002; Haug, 1993).

Ketones

Ketones such as acetone and methyl ethyl ketone (butanone) are quite volatile and have a “sweet” solvent-like odor (Miller, 1993). However, human sensitivity to these compounds is low (i.e. it takes a high concentration to detect them). Thus, although ketones are common byproducts of decomposition, they are not major odorants in themselves at composting sites. With other odorous gases, they can contribute to the overall malodor of decomposing organic materials.

Aldehydes

Several types of aldehydes develop in nature and from the decomposition of organic substances. Although it is concentration dependent, aldehydes of low molecular weight tend to have sharp objectionable odors while higher molecular weight aldehydes have a pleasant flowery odors (answer.com, 2005). Low molecular weight aldehydes include formaldehyde, acetaldehyde (ethanal) and propionaldehyde (propanal). The most familiar aldehyde is formaldehyde, which is recognized by its penetrating medicinal odor. Acetaldehyde is a diverse and widely dispersed substance . It has a variety of industrial uses and can occur in variety of materials including, fruit, coffee, alcohol, tobacco, wood smoke and engine exhaust. Its characteristic odor also carries a variety of descriptions including green, fruity, suffocating and garbage-like (Miller, 1993; answers.com, 2005; Goldstein, 2002). Its hedonic tone is apparently a matter of concentration and/or environment.

In addition to the preceding compounds, countless other volatile organic compounds, which humans can sense as an odor, can develop as organic material decomposes. These compounds may contribute to the overall quality of odors or become evident in unique and particular circumstances (e.g. a load of pesticide treated vegetation or solvents in MSW). Such compounds include aromatic chemicals (e.g. benzene, toluene) and phenols (e.g. methyl phenol, ethyl phenol). Epstein (1997) presents several lists of individual volatile organic compounds that have been identified in studies of emission from composting facilities. These compounds may be more relevant in their impact on healthy air quality (in enclosed spaces) than nuisance odors.

What Conditions Lead to the Formation of Odorous Compounds?

Odors experienced at composting facilities are a result of some combination of the compounds that have been discussed in the previous section. The compounds primarily responsible for malodors appear to be organic sulfides (particularly DMDS and DMS), mercaptans, amines and VFAs (Goldstein, 2002; Miller, 1993; Epstein, 1997). In addition, terpenes can contribute to the strength of the generally disagreeable soup of odors (Haug, 1993).

These offending compounds are either present in the greatest quantities, detectable at low concentrations, or have the strongest odor intensity and unpleasant hedonic tone. With certain feedstocks, ammonia and, to a lesser extent, hydrogen sulfide, are emitted in relatively high concentrations. They represent important nutrient losses and can cause problems related to air quality and on-site odors. However, they are not often contributors to off-site odors. The remaining compounds identified are either minor components of odor or cause problems in only a few specific situations. For instance, the odor of alcohol can be the problem when the pH drops excessively.

Knowing the chemicals that lead to odors, the subsequent question to ask is why and how do these offending compounds develop? The single broad answer is that they form from the natural, and primarily biological, decomposition of organic matter. Organic matter contains various combinations and species of carbohydrates, proteins and lipids, which decompose into simpler compounds. Odorous compounds can form via different biochemical processes, depending on the conditions (e.g. anaerobic vs. aerobic) and parent compounds available. Most of these chemicals are intermediate compounds in a progression of biochemical reactions; that is, they form and then change into other compounds. In a composting environment, compounds can transform in either direction: (a) they can degrade into simpler and more stable (i.e. more oxidized) molecules, such as carbon dioxide and water (and liberate energy); or (b) they can become the constituents of more complex organic compounds as microorganism use them for cellular material (thereby incorporating energy). The resulting compounds may or may not be volatile and odorous Therefore, an additional question to ask is how and why odorous compounds persist and accumulate to levels that result in detectable odors.

Important factors in the formation and fate of odor-causing compounds include the feedstocks, nutrient balances, oxygen, aeration, time, moisture, bulk density and porosity, temperature and pH.

Feedstocks

The type and mix of feedstocks composted are important determinants of odor. Feedstocks are probably the most important factor in determining what particular intermediate and potentially odorous compounds develop. The feedstocks establish the molecules and elements available for biochemical reactions, and their relative proportions. Thus, for example, feedstocks that do not contain appreciable amounts of sulfur will not produce appreciable quantities of organic sulfides. In addition, the relative mixture or proportions of different feedstocks influences what compounds ultimately form and accumulate (see nutrient balances below).

Miller (1993) provides examples of several precursors of selected odorous compounds, and these precursors are contained within the feedstocks. He identifies the amino acids cystine and methionine as sources of sulfur, with lesser amounts in other organic compounds. According to Miller, poultry manure is particularly rich in these amino acids and sulfur generally (0.56%).

Also, biosolids can have sulfur contents ranging from 0.3 to 1.2%. Other feedstocks identified include mixed food wastes (0.4%), other types of manure (0.25-0.3%) and garden trimmings (0.3%). Precursors identified for volatile nitrogen compounds include amino acids, proteins, urea and other organic compounds with N. Feedstocks high in nitrogen in manure (especially poultry), biosolids, grass clippings, fish wastes, blood, meat and many types of food processing wastes (Rynk, 1992). In general, any feedstock rich in protein can be expected to be a potentials source of volatile nitrogen (ammonia, amines, indoles), and possibly volatile sulfur as well (organic sulfides, mercaptans, hydrogen sulfide).

VFAs may form from any organic feedstock. However, they are more likely to accumulate in feedstocks with abundant and rapidly degrading carbohydrates, fats and oils, especially without sufficient oxygen (Miller, 1993). Phenol forms from the decomposition of lignin, which is abundant in wood (Miller, 1993). Particular terpenes emit from their associated plant materials, such as limonene from lemons, pinene from pine and cineol from eucalyptus.

In addition to its molecular composition, a feedstock's degradability also influences the creation of odorous compounds. Degradability refers to how quickly and completely a material decomposes. Feedstocks that degrade quickly tend to produce more odors, in part because oxygen is used up quickly and cannot be replaced fast enough. Hence, anoxic conditions prevail. In addition, with rapidly degrading feedstocks, the first stages of decomposition may simply outpace the subsequent stages, regardless of the availability of oxygen. Therefore, odorous intermediate compounds accumulate. As mentioned earlier, feedstocks that are rich in easily degradable carbohydrates can accumulate alcohols, which may be followed by aldehydes and ketones. In addition, quickly degrading feedstocks can lose porosity as they decompose, further challenging aeration. With most feedstocks, degradability is closely associated with lignin concentration (Richard, 2005).

It is important to recognize that when feedstocks are delivered to the composting site, they carry the associated odorous compounds, already formed or well on their way to being formed. Indeed, raw feedstocks are often the principle source of odors at composting sites (as opposed to odors that arise from the composting process). The amount, extent and impact of the raw feedstock odors depend on their volume and their previous history and handling. The following factors that influence the formation of odorous compounds during composting also influence the formation of odorous compounds within the raw feedstocks prior to composting.

Nutrient Balances

As feedstocks decompose, they provide nutrients to the decomposer organisms. The organisms use nutrients in proportion to their metabolic needs. Microorganisms do not readily process the excess nutrients, which then persist, possibly in a volatile form. Because carbon (C) is the element needed in greatest proportion, nutrient balances are often expressed in ratios with carbon.

Carbon to Nitrogen (C:N)

The prime example of the importance of nutrient balances is nitrogen (N). If nitrogen is abundant relative to carbon (e.g. C:N ratio < 20), volatile forms of nitrogen, mostly ammonia, are produced from the surplus N. However, if the same amount of N is available with a proportional amount of available C (or more), the available N is used by microorganisms and incorporated into their biomass (e.g. compost).

On the other hand, when the C:N ratio is very high, an excess amount of C exists. In this situation, decomposition slows because other nutrients limit the microbial metabolism. However, if easily decomposable C sources are present, volatile C compounds can accumulate and become noticeable as the dominant odor—VFAs, alcohols, phenols and terpenes, for example.

Carbon to Sulfur (C:S)

The same situation is likely to exist with other key elements like sulfur (S). Miller (1993) notes that stable organic matter has a C to S ratio of about 100:1. He implies that sulfur compounds would tend to volatilize from feedstocks with C:S ratio appreciably lower than 100:1. Because sulfur compounds are important odorants for organic materials, the C:S ration may be a useful indicator of odor potential. It is conceivable that the addition of sulfur-rich feedstocks, like gypsum, may push the C:S ratio high enough to cause odor problems.

Carbon Availability and Lignin

The C:N ratio is customarily calculated from laboratory analyses, which provide the total concentrations of C and N. However, total C is often a poor indicator of how much C is available to the microorganisms (Das, 2000). Many carbon-compounds are inaccessible to even microbial enzymes and cannot be degraded in the normal time frame of a composting system. This situation occurs to some degree with all feedstocks but it is particularly relevant to wood and some types of paper (e.g. newsprint). The determining factor appears to be the amount of lignin present (Kayhanian and Tchonbanoglous, 1992) Lignin is a complex organic compound formed in plants, and is especially abundant in wood. It is difficult to biochemically decompose. Lignin also physically blocks microorganisms from attacking other more readily degradable organic compounds, like cellulose (Richard, 2005).

In feedstocks that have a high lignin content, the C:N ratio (and the C:S ratio) is artificially high. The *effective* C:N ratio is actually much lower because a large portion of the carbon is unavailable to the microorganisms. Tchobanoglous et al. (1993) suggests determining the biodegradability of a feedstock based on its lignin content according to the following empirical equation.

$$BF = 0.83 - (0.028) \times LC$$

Where BF is the biodegradable fraction of the volatile solids and LC is the lignin content of the volatile solids as a percent of dry weight. The numbers 0.83 and 0.028 are empirical constants.

Das (2000) presents a procedure for adjusting the C:N ratio using the above equation and work published by Kayhanian and Tchobanoglous (1992). However, it should be recognized that particle size also affects the availability of carbon and other nutrients (larger particles reducing availability). Richard (2000) offers a good review of the effect of lignin and other factors on biodegradability, carbon availability and C:N ratio.

Oxygen (aerobic vs. anoxic vs. anaerobic decomposition)

Oxygen is a critical factor in the genesis of composting odors. Oxygen determines the biochemical processes at work (i.e. anaerobic vs. aerobic) and the compounds that result. Many odorous compounds can form simply because organic materials degrade –in both aerobic and anaerobic environments. However, the situation is much more severe when anoxic or anaerobic conditions exist. The terms anoxic and anaerobic often used interchangeably to describe no-oxygen conditions; even though, they refer to different metabolic modes. Anoxic refers to the metabolism where microorganisms use an oxygen bond in other molecules such as NO2-3 (nitrate) as the terminal electron acceptor; whereas, anaerobic means microorganisms use other molecules.

In the presence of oxygen, many of the odorous compounds do not form at all, or they are so transient that they can be said not to form. When sufficient oxygen is present, nearly all of the odorous compounds that do develop ultimately transform into non-odorous products (ammonia being an exception). Without enough oxygen, odorous compounds form and accumulate more readily and to a greater extent. This condition greatly increases the intensity, unpleasantness, and duration of the odors that occur. Maintaining adequate oxygen levels, i.e. aerobic conditions goes a long way toward avoiding odor problems during composting and correcting problems that arrive with anaerobic feedstocks.

The odorous compounds that are problems essentially *only* when anoxic and anaerobic conditions prevail include hydrogen sulfide, organic sulfides (e.g. DMDS, DMS) and VFAs. Compounds that might be evident in aerobic situations but reach problem levels under anoxic and anaerobic conditions include amines, indoles, mercaptans, alcohols, ketones and aldehydes. Although oxygen advances the degradation of terpenes, they are often detectable in any case when they are liberated from plant cells.

Aeration

Aeration is the mechanism that brings and distributes oxygen-carrying air to the mass of composting materials. Aeration also removes heat, moisture and other gaseous products of the decomposition occurring within the mass. Aeration delivers the fresh air and removes the exhaust air through the intricate network of air-filled pores within the mass. From those pores, oxygen diffuses into and through the films of moisture that cling to the solid particles that are undergoing these chemical transformations. In composting, aeration occurs by natural or passive air movement (thermal convection, diffusion, wind) or by forced aeration (fans).

The primary effect of aeration on the formation of odorous compounds is related to its impact on oxygen concentration, as discussed above. Odorous compounds can form in problem quantities if the aeration fails to deliver enough fresh air and oxygen or if it fails to distribute the air evenly. In the latter case, odorous compounds can develop in the air-starved *sections* of the composting mass. If there isn't sufficient oxygen surrounding those sections to degrade the odorous compounds, then odors are released when those sections are exposed or if the aeration system carries those compounds to the ambient environment.

A secondary affect of the aeration system on the formation of odorous compounds concerns temperature and moisture. Removing excess moisture and heat (thus controlling the temperature) are additional functions of aeration. The effects of temperature and moisture on the formation of odorous compounds are discussed below.

Aeration is an important factor in the transport of odorous compounds from the composting mass to the outside environment. The aeration system may remove an odorous compound before it has the opportunity to further decompose in place (Elwell et al., 2004). Odor released due to aeration is discussed in a later section.

Turning

For passively aerated composting methods, like windrow composting, turning is the primary tool for operators to control the process, and thus the formation of odors. Turning introduces fresh air, improves the distribution of water and nutrients and may improve porosity in some cases. It advances the composting process and improves odors in the long run. Even with forced aeration, turning overcomes the stagnation exhibited by static composting and advances the process. However, at the same time, turning opens the interior of piles and windrows and releases trapped odorants.

The conditional effects of turning on odors are evident from a pair of excellent studies of green waste composting from the late 1990s. Buckner (2002a, 2002b) examined how green waste composition (e.g. grass, leaves, wood chips) and turning frequency influenced oxygen concentration and odor emissions. Michel et al, 1996 examined the effects of these factors plus pile size on odors, oxygen and other composting process parameters. Together, the two studies suggest that turning has the following effects.

- Turning stimulates decomposition and oxygen demand.
- Turning has little impact on internal windrow/pile temperatures. Overall, temperatures recover to pre-turning levels, achieving neither a lasting heating nor cooling effect.
- The frequency of turning has little effect on internal oxygen concentrations. Any positive effects on aeration rate may be negated by the higher oxygen demand as the process is stimulated. In fact, Buckner found generally higher oxygen concentrations in windrows turned once per week compared to six times per week. Feedstock composition and porosity have a greater effect on oxygen concentration than turning frequency.

- The effects of turning on odors depend on the feedstocks and their porosity. Turning is more effective at suppressing odors with feedstocks that decompose quickly and without the benefit of good porosity (e.g. grass and leaves). On the other hand, these types of feedstocks release more odors upon turning, regardless of the frequency.

- Odors are greatest with the first turning and subside quickly with subsequent turnings. Odor spikes can occur later with subsequent turnings if the turning schedule is relatively infrequent (e.g. weekly vs. daily).

- Daily or almost daily turnings are required to maintain elevated oxygen concentrations indicated of truly aerobic conditions during the early stages of composting (Michel, 2002). However, even with infrequent turning (e.g. monthly), decomposition tends to be primarily aerobic rather than anaerobic, supported by passive air movement and diffusion.

- Turning does not necessarily improve the porosity of the feedstocks by fluffing, as has been suggested (Rynk, 1992). In fact, Michel et al. found that the chopping effect of turners reduces particle size in mixtures of leaves and grass. Thus, these mixtures become denser shortly after turning. The influence of turning on porosity, its "fluffing effect," may be dependent on the condition of the feedstocks. Turning may temporarily increase the porosity (i.e. decrease the bulk density) of feedstocks, like manure, that already have fine particles. With bulky feedstocks that easily shred, like leaves, turning produces "reverse fluffing"—they increase in density and decrease in porosity, Michel et al. discovered.

Time

Time is an odor factor because decomposition is not a steady process. It advances quickly at first and gradually slows in pace. In the early stages, the most readily degradable compounds decompose in a fast and accelerating pace. In this time, intermediate compounds form and transform, temperature climbs and oxygen demand is great. As the process continues, the moderately degradable compounds in the feedstocks begin to breakdown along with the resulting intermediate compounds. The biological activity and oxygen demand settle to a high but steady pace. Over time, the rate of decomposition and oxygen demand gradually fall to relatively low levels until the compost matures.

The connection to odor is that odorous compounds are formed and/or released in greatest quantities in the first stage of the process, during the same period that the need for oxygen is greatest. Therefore, the likelihood of odors is greatest during the first days, and up until the first week or two of composting. Indeed, the process may have started before feedstocks arrive at the site, depending on how and how long they were stored and handled. Several investigators have tracked emissions of odorous compounds over time and concluded that most odors are released in the first 3 to 14 days of composting (Epstein, 1997).

The high early emissions of odorous intermediate compounds rather than oxidized end products (e.g. CO_2 and H_2O) may be due to the high oxygen demand at this time. The aeration mechanisms may not be able to supply enough oxygen to meet the demand. Alternatively, regardless of the mode of aeration, the rate of oxygen diffusion from the interstitial pores to the microorganism may not be fast enough to match their O_2 consumption (see Moisture section below).

Yet another possibility is that the subsequent steps of decomposition are not keeping pace. For examples, given the large amount of substrates in the feedstocks, one set of microorganisms may be forming mercaptans faster than the next set can oxidize them. In any case, with time, fewer odorous intermediate compounds are emitted.

Moisture

Moisture is related to odors in several ways—in its effects on aeration and oxygen diffusion; in its influence on decomposition; and in regard to retaining volatile compounds in solution.

Moisture greatly effects the ”oxygen status” of decomposition—that is, whether or not, oxygen is available to the decomposer microorganisms and how much oxygen is available. It impacts oxygen first in its effect on aeration -- the movement of air into the pore spaces of the composting mass.

If too much moisture is present then water occupies the pore spaces (reducing “free air space,” or FAS) and makes it more difficult to oxygen-carrying air to enter the mass, and for carbon dioxide and other gases to leave. The second effect is for moisture to interfere with the diffusion of oxygen from the pore spaces through the liquid film (i.e. water solution) surrounding the solid particles that are decomposing.

The decomposer microorganisms inhabit that liquid film and rely on diffusion to deliver oxygen. Because diffusion of oxygen through water is relatively slow, a thicker film, due to higher moisture content, reduces the oxygen supply to the microorganisms. Via both effects, higher moisture contents lead to lower oxygen levels and more anoxic and anaerobic environments.

On a practical level, the moisture threshold for avoiding anaerobic conditions is approximately 60% (wet basis). However, this number represents a compromise and a practical target. The optimal moisture content depends on the feedstocks (e.g. particle size, degradability) and the stage of composting (Richard et al., 2002).

Furthermore, it does not ensure that anaerobic conditions are avoided. It simply reduces the occurrence to a practical and tolerable level. Overall, excessive moisture (> 60%) increases the occurrence of anaerobic conditions and the formation and persistence odorous compounds (Wilber and Murray, 1990).

Moisture is necessary for active decomposition. More moisture generally advances the rate of decomposition and thus increases the generation of the products of decomposition. If the feedstock is dry, decomposition proceeds slowly or not at all. Odorous compounds that result from decomposition are not emitted from dry materials. However, dry materials can emit odorous compounds that are inherent to the feedstock, such as terpenes from wood and green wastes.

In some cases, the release of some odorous compounds can conceivably increase as the material dries. As the moisture content decreases, the concentration of potentially volatile compounds in the remaining water solution increases. This increase can shift the equilibrium between soluble and volatile forms, encouraging volatilization. For example, as moisture decreases ammonium in solution becomes concentrated and, in turn, some ammonium converts to ammonia. Conceivably, the same situation can occur with terpenes in freshly cut pine branches. The impact of this drying effect on composting odors is probably small because it represents a situation where odor problems are not likely to be serious.

Bulk Density and Porosity

Bulk density affects odors because it influences aeration and oxygen concentration. Bulk density is determined by the size and shape of particles and the density of the individual particles. These factors also determine the material's *porosity* and *free air space* (FAS). Porosity is the proportion of a bulk material occupied by pore spaces. FAS is the pore space that is not filled with water. Bulk density and porosity are closely related (Day and Shaw, 2001). Moisture is an important factor in determining bulk density, and it can confound generalizations about how bulk density affects aeration, oxygen and odors. However, if one considers "dry" bulk density, or assumes a moderate level of moisture, some generalizations are reasonable.

Dense feedstocks tend to have small particles and narrow pore spaces between particles. The closely-spaced matrix of particles offers considerable resistance to air movement within the materials. This situation inhibits both passive and forced aeration and reduces the resupply of oxygen. In addition, at a given moisture content, as the bulk density increases there is generally a greater mass of organic matter to decompose—per unit volume.

Thus, oxygen demand and oxygen consumption are greater—per unit volume. In short, anaerobic conditions are more likely to occur in feedstocks and feedstock mixes as the bulk density increases. Buckner (2002a, 2002b) found that odors from composting grass clippings were better controlled using mixtures with higher proportions of wood chips. Similarly, Epstein (1997) reported the data in Table 4 showing an increase in mercaptans with increasing bulk density of a mixture of green waste and food residuals (produce wastes).

In comparing the last two columns, note that bulk density alone is not the only factor. The higher proportion of food waste in the 4:2 mix ratio elevated the mercaptan emissions even though the bulk density was slightly lower than the 4:1 ratio mix (although for practical purposes the bulk densities of the two mixes are equivalent).

For this reason, dense feedstocks are typically mixed with light or bulky feedstocks (i.e. bulking agents) to reduce the overall bulk density and improve porosity and aeration. Generally composting recommendations suggest that bulk density should be less than 1000 lbs/cu. yd. (Oshins, 2006).

Table 4: Effect of initial bulk density on the formation of odorous compounds (mercaptans)

Initial mix ratio of green waste to produce (food) waste	**4:0**	**4:1**	**4:1**	**4:2**
Preprocessing	None	None	Hammermill - all material	Hammermill - all material
Bulk density – lbs/yd^3 (kg/m^3)	255 (151)	425 (252)	1273 (755)	1187 (704)
Oxygen concentration (sample at 3 ft. high and 4 ft, deep)	20%	19%	0.3%	0
Total mercaptans **(sample at pile surface)**	**0.2**	**0.5**	**25**	**100**

Source: adapted from E&A Consultants, Inc., 1993, after Epstein, 1997.

Temperature

Temperature has numerous effects on the composting process and the compounds that arise. Temperature influences the composition of the microorganisms (Miller, 1993; Strom, 1985), the rate of biological activity, the rate of chemical reactions, moisture loss, aeration (e.g. thermal convection), oxygen diffusion and the transport of gaseous compounds.

Up to a limit of approximately 60°C (Miller, 1993), increasing temperature generally increases biological activity and, hence, the rate of decomposition. Therefore, all other things equal, a rise in temperature also brings a rise in oxygen demand. Fortunately, this situation (higher temperature – faster decomposition) is usually accompanied by greater aeration. With passive aeration, the higher temperature tends to increase air movement due to thermal convection (assuming that there is enough porosity to accommodate the additional air flow).

With forced aeration, when the rate of composting increases the aeration system is activated more often because aeration is usually controlled by temperature for cooling purposes. On one hand, as temperatures increase, potentially odorous compounds form faster due to faster rate of decomposition and greater oxygen demand (at least up to 60°C or so). On the other hand, the additional aeration and/or the faster decomposition of the odorous intermediate compounds tend to reduce the potential for odors. In regard to odor formation, some evidence suggests that the "other hand" prevails – that increasing temperatures reduce odors.

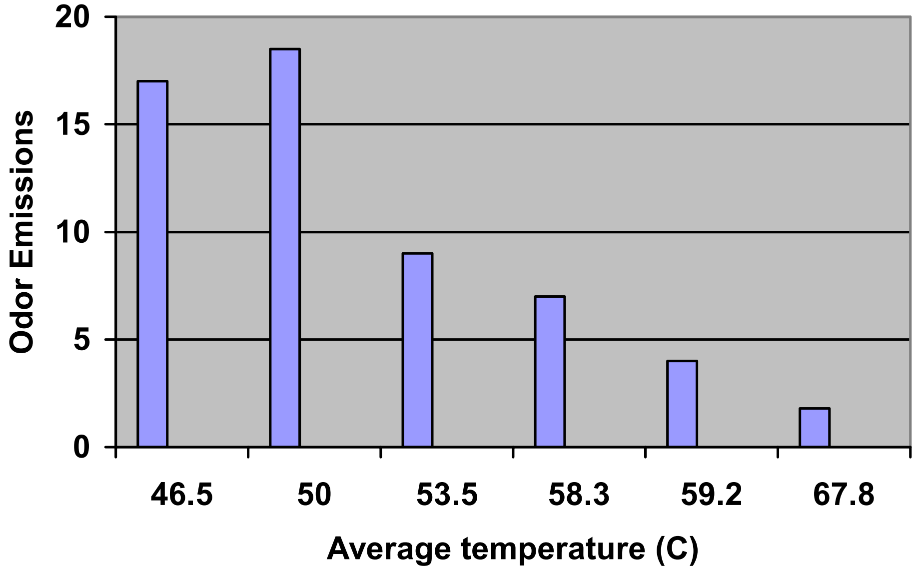
Epstein (1997) reports a study by Wilbur and Murray (1990) that shows decreasing odor emissions at a biosolids composting facility with increasing temperature, from 46 ºC up to 68 ºC (Figure 1). At the upper limit, these results seem to contradict citations by Miller (1993) that indicate a reduction of odors below 60°C. However, the upper temperature threshold for composting is still debated. Several researchers have suggested thresholds greater than 60°C (Epstein, 1997).

Chemical reactions also increase with temperature (by about a factor 2 for every 10°C rise). At very high temperatures, chemical reactions can generate odorous compounds, at a faster rate, without the counteracting benefit of microbial oxidization of those compounds. For example, Derikx et al (1991) reported the increasing rates of DMDS generation with increasing temperatures up to 90°C. At these high temperatures DMDS can form more rapidly but cannot be degraded biologically. Thus, it accumulates to a higher concentration.

Temperature has another profound effect on odors – it increases the vapor pressure of most compounds. Volatile compounds volatilize and become air borne more readily as temperature increases. In fact, there is a double penalty in this relationship because, as noted earlier, aeration also tends to increase with temperatures. Thus, with higher temperature, volatile compounds become more volatile and there is also more air flow through the material to carry those volatile compounds toward someone's nose. This effect has more to do with the impact of odorous compounds than their formation (see following sections).

Generalizations about the relationship of temperature to odors are difficult, given the multiple influences that temperature has on decomposition and odor transport. The net effects likely depend on specifics such as the particular volatile compounds present, the stage of composting, the availability of oxygen, exposure to the ambient environment and the feedstocks and their degradability. In general, if conditions (e.g. oxygen, moisture, pH) are favorable for composting, odorous compounds generally decrease with increasing temperatures, at least up to some maximum between 60°C and 70°C.

Figure 1: Effect of temperature on odor emissions



Source: from Wilbur and Murray, 1990, after Epstein, 1997.

pH

pH indicates the acidity and alkalinity of the chemical environment or solution. It is a measure of the relative concentration of hydrogen (H) and hydroxide (OH) ions. pH affects, and is affected by, the chemistry and biology of composting. It helps determine the microorganisms that thrive and the direction and nature of chemical reactions. Specific enzymes tend to have relatively narrow pH ranges (Sawyer and McCarty, 1978).

Because of the inherent robustness of the composting process and the great diversity of microorganisms that participate, composting takes place over a broad range of pH levels (Oshins, 2006). Still, there are benefits to keeping the pH closer to neutral (6.5 to 8.0). In addition, extreme pH levels can substantially inhibit biological activity, which is normally a problem but can also be used to one's advantage.

pH shifts the chemical equilibrium of several important volatile compounds. At high pH (> 8), soluble ammonium (NH_4^+) is converted to volatile ammonia. The smell of ammonia is particularly evident with feedstocks that have a high pH, including poultry manure, and feedstocks that include wood ash or lime (e.g. lime-treated biosolids). In contrast, lower levels of pH (<7) favor the formation of hydrogen sulfide, relative to the soluble sulfide ions, S^{2-} (Sawyer and McCarty, 1978, p. 478). In the absence of oxygen and at acidic pH (<7), hydrogen sulfide is likely to form, and smell, if sulfur is available. At higher pH (> 8), hydrogen sulfide odors are unlikely in any case.

The combination of low pH and anoxic conditions constitutes a "reducing environment." In reducing environments, incomplete biological processes prevail including anaerobic decomposition and fermentation. In this situation, chemical elements tend to exist within "reduced" states, meaning that they are not completely degraded. Reduced compounds retain some energy. When oxygen is present, they are further degraded (i.e. oxidized) by organisms.

Thus, reduced compounds are often termed intermediate compounds. Many odorous compounds identified with composting are intermediate and reduced forms, including hydrogen sulfide, organic sulfides, amines, ammonia, VFAs and alcohols. Reducing potential is influenced by *both* the concentration of oxygen and the pH but extremes of one or the other can lead to reducing conditions. As previously mentioned, alcohol can accumulate during the early stages of composting when the pH drops to a very low level. The alcohols result from fermentation of the organic substrates and then accumulate because of the lack of either oxygen or biological activity (due to the low pH).

Composting feedstocks have a strong buffering capacity that tends to resist changes in pH. However, large additions of very acidic or very basic materials can produce extreme changes. Lime and wood ash have been intentionally added to raw composting feedstocks with the purpose of temporarily slowing the biological activity and prevent the formation of odorous compounds (Lystad, et al., 2002; Campbell et al., 1997).

For example, Lystad (2002) reported results of a project at a composting facility in Norway in which lime was added to food and green wastes ("biowaste") to raise the initial pH to 11.9 in order to control the odor emissions during handling and the early stages of composting. The investigators reported that the overall odor situation improved and that the pH recovered to levels below 8 after a few days of composting in an enclosed vessel (and before the partially composted feedstocks were placed in outdoor windrows). Campbell et al. (1997) used a similar approach, adding wood ash to biosolids to improve odor performance. While the high pH amendments had little impact on the compost quality in the project in Norway, Campbell et al. reported that the finished compost had a lower maturity and higher final pH and salts due to the wood ash additions (Das, 2000).

Degradation versus Dispersal (exposure and transport)

Volatile intermediate compounds eventually degrade within the composting mass, given a population of suitable microorganisms and enough time for oxygen to find its way to the compounds. In the meantime, the compounds accumulate within the solution or within the pore spaces of the composting mass. Alternatively, volatile compounds can be carried away by the aeration system or volatilized upon exposure to the ambient environment via agitation or turning. Thus, the fate of odorous compounds, once formed, also depends on the aeration system and the extent and timing or turning and other means of agitation.

The dispersal of odorous compounds can have positive or negative effects on the facility depending on the specific situation. For instance, if the concentration of odorous compounds is high, their dispersal may cause odor problems. If compounds are continually or frequently dispersed at low concentrations, below detection thresholds, the dispersal may reduce their accumulation and lower the potential for problems when the composting mass is eventually disturbed. This line of thinking raises the question of whether frequent turning is preferred to infrequent turning.

What Conditions and Factors Lead to Off-Site Impacts (For Example, Odor Complaints)?

In order for an odorous compound, or a soup of odorous compounds, to become odorous, it must first volatilize, become airborne and escape into the environment. Then, it must be transported to a person, remaining in concentrations sufficiently high enough to be detected and to be considered objectionable by that person. Thus the necessary set of conditions that leads to an odor impact on the neighboring community includes:

- Odor source (in which odorous compounds)
- Odor emissions
- Odor transport
- Odor persistence and detection

The previous chapters of this report discussed the formation, volatilization and nature of odorous compounds associated with sources at composting facilities. This section focuses on the sources, emissions, transport and fate of these odorous compounds in the environment. The succeeding chapter concerns how people perceive and react to odors.

Odor Sources

Any location within a composting site that harbors organic compounds is a *potential* odor source including raw feedstock piles, active composting piles and windrows, curing piles, finished compost piles, grinding areas, biofilters, runoff storage ponds, puddles on the site and even surfaces where organic materials have been stacked. Some of sources present a much greater risk than others and these sources tend to be the primary contributors to odors. In general, materials in the early stages of decomposition present the greatest risk of odors because they generate greater quantities of natural and intermediate volatile compounds and they need more oxygen to remain aerobic. Therefore, raw feedstock piles and relatively “young” composting windrows and piles are usually the sources of most concern, and deserve the most scrutiny. However, other sources cannot be ignored and may even emit a greater amount of odorous compounds than composting piles. Much depends on the specific conditions.

Epstein (1997) reports data from a study by Toffey et al. (1995) of odors from an aerated static pile from a biosolids composting facility. The study reports that the mass of odors released from biofilters and curing piles were comparable, and in some cases greater, than the mass emitted from composting piles (aerated under negative or suction air flow). In part, the contribution of odors from the biofilter and curing piles were due to air flow patterns and exposed surface area of these sources.

Elitzer (1995) shows collective emissions data of numerous volatile organic compounds at various points in several MSW composting facilities (some including yard trimmings or biosolids). Although the trends differ slightly among the various compounds, the highest emissions tend to come from the feedstock tipping floor, the output of composting digester drums (first stage of composting) and from newly formed composting piles. For some compounds, emissions were higher from “mid-aged” and “old” piles than fresh piles but generally emissions decreased with pile age and were lowest in the curing piles.

As indicated by the Toffey study, odor treatment devices like biofilters, and chemical scrubbers as well, can be relatively prominent contributors to site odor emissions, where they are used. This fact does not imply that they are ineffective, though poor design and operation would certainly increase the emissions. On the contrary, biofilters and scrubbers have been found to substantially decrease total odor emissions (Kuter, 1990; Williams and Miller, 1993).

However, because exhaust air from piles, buildings and other enclosures is delivered to these treatment devices, they become points of concentration for odor emissions, even after they substantially remove and treat odorous compounds. At the same time, the odor emissions decrease from the other sources. In a sense the treatment devices become a point source of odors. This situation is especially true for scrubbers that discharge treated air through an exhaust stack (as opposed to the broad surface of a biofilter).

Scrubbers, and even some biofilters, act like point sources of odor. Buildings and in-vessel exhaust outlets are other possible point sources. However, most other potential odor sources at a composting facility are considered area sources. Area sources emit volatile compounds over a broad area without a distinct and continuous air current (as in an exhaust stack). Emissions from area sources are more difficult to measure, quantify, predict and control.

The emissions from area sources tend to be inconsistent and more dependent on ambient conditions than point sources, although computer models often assume a constant average emissions rate (Brant and Elliott, 2004). Prominent area sources include storage piles, windrows, open aerated piles and bins, curing piles, processing and handling areas, water bodies (e.g. ponds) and the site itself.

Water storage ponds can emit odors if they become overloaded with organics to the point that oxygen is depleted and the water body becomes anoxic and anaerobic. Volatile odorous intermediate compounds form within the water just as they do within the solid composting mass, perhaps even more readily. The same situation exists for small puddles and water-soaked soils that remain on site.

It has been suggested that the site itself can become a large area source for odors as organic liquids and small solid particles seep into the soil and pad surfaces overtime, more so at locations where feedstocks and composting piles are placed. Thus, the site can conceivably acquire a “resident” odor as the embedded organics decompose and volatile compounds are continually formed and emitted. This situation might explain the increase in odors occasionally reported following rain at some facilities (Rynk, 2004). The contribution of site surfaces to facility odors has not been reported in literature so the concept remains a matter of conjecture. Given the other large areas of actively decomposing material at most facilities, the site itself is probably a relatively small contributor to the total odor.

How much odor a given source contributes to the overall odor condition depends on many factors, including process conditions, oxygen, aeration, volume and exposure (e.g. agitation, surface area). In addition, while the odor produced by any single source may be inconsequential, the combined emissions from several sources on a site may bestow the facility with an “ambient” odor that can periodically lead to off-site problems. Such odor problems may occur only during unfavorable weather conditions and/or when activities at the facility raise the ambient odor level above some critical threshold.

Odor Emission

Once formed within a mass of decomposing organic feedstocks, an odorant can continue to decompose, remain within the mass to decompose later or escape into the environment. Its escape may come relatively slowly through exposed surfaces via passive mechanisms, typically diffusion or thermal convection. Or, active forces like agitation and forced aeration can hasten its liberation. Any factors that either accelerate or retard the decomposition of the odorant also play a role in the potential for the odorant to become an odor. Odor problems do not occur when an individual molecule of an odorous compound escapes the facility. The problems occur when odorant molecules leave in huge numbers.

Volume/Mass

Another relevant factor in the release of odors from a facility is the amount of material on site, whether the amounts is expressed as volume (e.g. cubic yards) or mass (e.g. tons). Odor problems have been attributed to facilities increasing the amount of feedstock accepted (Rynk, 2003). There are several reasons that the amount of material influences odors.

First, a greater amount of material potentially generates a larger inventory of volatile compounds. Second, more material translates to a larger surface area for the potential release of odors. Third, as the material volume increases so does the workload and pressure on management to keep the operation running well. How much a factor the resident mass/volume depends on the nature of the facility (e.g. enclosed vs. open; isolated vs. populated area) and the composting methods employed (e.g. large piles vs. small piles).

No rationale exists for determining volume (or mass) limits that would minimize odors. Furthermore, there are no universally accepted standards. Nevertheless, some jurisdictions have established guidelines for the purpose. For example, Massachusetts

Department of Environmental Protection (MDEP) professionals use an unofficial benchmark of 3,000 to 6,000 cubic yards per acre (Martinson, 2003). This range is drawn from the experience of the DEP's composting program staff, considering the size of windrows and piles that can be comfortably managed by facility operators. The Michigan Compost Operator Training Manual (Michigan Composting Coalition) suggests the following maximum annual throughputs (volumes accepted per year) as reasonable to avoid odors:

Low intensity management: 3,000 cy per acre per year

Medium intensity management: 5,000 cy per acre per year

High intensity managemnt: 8,000 cy per acre per year

In this case, "management" refers to the type of composting method used and the level of oversight and manipulation. The manual does not provide for either a technical or historical basis for the foregoing volume limits. Again, there is no rational or data to support volume limits for odor control. One can establish maximum sizes for windrows and piles and then calculate the corresponding volume per acre. However, setting maximum windrow and pile sizes is arbitrary and does not take into account the site conditions, process management and feedstocks and other conditions that can vary among facilities.

Surface Area

Volatile compounds escape from surfaces of windrows, piles and bins. Therefore, the amount of surface area exposed to the environment is a very important factor in the odor equation. All of the area sources identified earlier, including water and soil surfaces, release volatile compounds roughly in proportion to the exposed surface area. However, the geometry of piles and aeration patterns affect the emissions as well. For example, in passively aerated piles and windrows, more volatile compounds tend to escape with the air flow through the ridge than the sides. Exposed surfaces are especially critical for sources that generate a large amount of volatile compounds.

Thus, an expansive feedstock pile is worse than an expansive pile of finished compost. Small piles (i.e. short piles) have a greater surface area to volume ratio than large piles (i.e. tall piles). Thus, one can argue that odors are better contained by large piles. In fact, some composters do make this argument.

However, large piles are more difficult to effectively aerate and anaerobic conditions are more pervasive. Thus, very large piles of actively decomposing materials are generally discouraged. Forced aeration is one means to increase pile size, limit surface area and maintain acceptable aeration within the pile (see forced aeration section below). Another alternative is to limit the exposure of surfaces by containing materials within bins, buildings, vessels or flexible envelopes.

As Haug (1993) describes, the "surface odor emissions rate" or SOER is a useful technique for conceptualizing, measuring and modeling odor emissions from surface area sources like windrows, piles and biofilters. The SOER encompasses both the concentration of the "odor" and its rate of emissions per unit area. The SOER can be measured using an enclosed sampling hood and drawing air off the surface at a known rate and capture the sample in a tedlar bag or canisters. The procedure is not as straightforward as described.

The technique can be confounded by several factors, including variations in emissions rates over the surface. Therefore, several standard procedures have been established, although these procedures continue to be refined. For example, the South Coast Air Quality Management District (AQMD) uses a flux-chamber method that was originally developed by the U.S. Environmental Protection Agency to collect air pollutant emissions from contaminated lands.

Agitation/Turning

As noted above, volatile compounds escape from exposed surfaces. To do so, these compounds must first find their way to the surfaces from the interior of the pile. Otherwise, they remain trapped within the confines of the mass and eventually transform into innocuous forms (e.g. are metabolized or oxidized).

Compounds can migrate to the surface by diffusion or be carried in air currents and physically transported by agitation. Diffusion is a slow process that allows ample opportunity for the volatile compounds to be adsorbed and degraded within the mass. In contrast, agitation of the materials abruptly exposes the compounds to the surrounding. At that point, the volatile compounds that have accumulated within, volatilize and escape abruptly and in high concentrations. However, the emission of odors decreases quickly soon after the immediate exposure and then gradually returns to a relatively constant level (Lacoboni et al. 1980).

In composting, turning is a prime example of such agitation but materials are also disturbed during mixing of feedstocks, grinding, screening and simply materials handling. For this reason intense odors are typically experienced following turning and other means of agitation. The amount and character of the odors released by agitation depends on the nature and state of the materials. Raw feedstocks, actively decomposing materials and/or materials in an anaerobic state release more volatile compounds, and more odor, upon being disturbed than materials that are relatively stable or well aerated.

Because turning also introduces air, improves the distribution of water and nutrients and may improve porosity in some cases, it advances the composting process and improves odors in the long run. However, there is some debate about whether the frequent release of moderate odors from frequent turning is more damaging than the infrequent release of strong odors from infrequent turning. Composting operators have expressed contrasting opinions. Research provides little guidance on this point.

Lacoboni et al (1980) measured odors released from six windrows containing biosolids at different turning regimes (Table 4). Looking at only the averages among the pairs, there is a trend that shows more odor and stronger (i.e. peak) odor *per turning* as the frequency of turnings decreases. However, as the number of turnings increases, the *total* amount of odors released due to turnings (over all turnings) is slightly greater. Also, total emissions from the windrows (turning plus passive surface emissions) are nearly the same for all windrows. On the other hand, the variability of the results for individual windrows defies generalizations.

Therefore, from Lacoboni et al.'s results it is difficult to say whether more frequent turning has a positive or negative effect on odors. It very likely depends on the specific situation of the composting operation and whether the facility has flexibility in scheduling turnings. For example, the peak odor emission after turning may be the most important parameter if odor complaints tend to occur from periodic strong odors while the total emissions are more important for facilities that are plagued by a constant border line odor. It should also be noted that the number of turnings of the biosolids windrows monitored by the Lacoboni study are greater than those for the typical green waste and agricultural composting windrows. Five or six turns are more typical in the latter cases (Rynk, 1994).

Table 5: Odor emissions from turned windrows composting biosolids

Windrow Number	Ambient Odor Emissions (ou/m^2)	Peak Odor Emissions after Turning (ou/min./m^2)	Odor Emissions per Turn (ou/m^2)	Number of Turns	Odor Emissions as a Result of Turning (ou/m^2)	Total Odor Emissions for a 6-Week Composting Cycle (ou/m^2)
1	2809	0.798	23.97	30	719	3528
2	2809	0.985	29.54	18	532	3341
3	2809	2.5053	61.59	12	739	3548
4	2809	0.502	15.05	30	451	3261
5	2809	1.133	34.00	18	612	3421
6	2809	0.771	23.13	12	278	3087

Source: from Lacoboni et al, 1980, after Epstein, 1997.

Aeration

Aeration ventilates the composting material. It brings in fresh oxygen-rich air and removes air that contains the products and by-products of decomposition, including volatile and odorous compounds. The air stream leaving the composting windrow/pile releases those odorous compounds into the surrounding environment unless it is captured and treated (e.g. in a biofilter). Again, the type and amount of odorous compounds in the exiting air stream depends on the feedstocks, their stage of decomposition and the aerobic/anaerobic state. There are two mechanisms of aeration in composting, passive and forced. Both carry odors into the environment.

Passive

Passive aeration relies on natural convection, wind and diffusion to move air in and out of the pile. Natural convection is largely driven by the tendency of warm air to rise up and out of the top of windrow piles and bins. Cool fresh air enters along the sides and edges to fill the vacuum. The air flow into the pile is determined by the temperature difference between the internal pile and the ambient air plus the porosity of the matrix of materials within the pile.

Passive aeration occurs naturally in any standing pile of materials (feedstocks, composting, curing and stored compost) and exposed surfaces in bins. The exiting air rises unevenly from the surface of the material, but more prominently near the peaks and ridges. The exhaust and potentially odorous air cannot be captured unless the material is totally contained in a building, vessel or other envelope (e.g. covers, plastic pods).

In general, strong passive aeration should be encouraged to manage odors because it reduces anaerobic conditions. Composters promote passive aeration primarily by establishing a porous matrix of materials. It also helps to build piles to a moderate size that strikes a balance between retaining heat and promoting air exchange. Smaller piles limit the depth that the air must penetrate and also increase the exposed surface area per unit volume of material.

Although more aeration is generally better, passive air movement does carry odorous compounds out of the pile. The emission of odors is most critical at the early stages of composting when highly degradable feedstocks quickly consume the available oxygen and high temperatures encourage strong air movement. To minimize the odors carried with the exiting air, the exposed surface of piles and bins are often covered with a layer of porous and adsorbent amendments, such as wood chips. The amendment layer tends to adsorb many of the odorous compounds yet it is porous enough to permit strong aeration.

Forced

Forced aeration uses fans to push or pull air through the composting mass. It is used for composting material in freestanding piles (e.g. aerated static piles), partially enclosed bins and in many in-vessel composting techniques including aerated containers, rotating drums and agitated beds. In addition, forced aeration is employed for biofilters and sometimes used to aerate curing piles.

Compared to the passive alternative, forced aeration is a more certain approach to insuring that the materials remain aerobic. The use of fans to drive aeration removes the reliance on natural mechanisms. Thus, composting can take place in a larger pile, with a smaller surface area to volume ratio. However, steady and vigorous airflow from forced aeration can engulf and transport a large amount of volatile chemicals with it. Hence, the exhaust air can become an odor source in itself. For that reason, many composting facilities pass the exhaust through treatment devices like biofilters and chemical scrubbers. A greater airflow than necessary is a disadvantage, because it leads to either more odor release or greater demands on the treatment device.

There are several modes of forced aeration—positive or negative, intermittent or continuous. In the positive mode, a fan forces air outward from the base of the composting materials. The exhaust air discharges through the outer surfaces. It cannot be captured unless the material is contained in a building, container or vessel. In the negative mode, the fan draws or sucks air from the outside through the materials and into a collection pipe, vent or plenum at the base of the material. The exhaust air is concentrated in the collection system and this can be directed to a treatment device and/or discharged in a controlled manner. (Note: there are other variations to the geometry and layout of the ventilation networks).

In most actively composting materials, the amount of air moved through a composting mass is determined by temperature that is the need to remove heat to maintain favorable temperatures. Less air is needed to supply oxygen and remove moisture. Thus, forced air is typically turned on and off based on temperature. Another option is to run the fan continuously at a low rate and increase the rate when greater air flow is required for cooling.

Researchers at Ohio State University (OSU) have published a strong body of work describing the effects of forced aeration on odor formation and emissions in addition to nitrogen loss and other composting parameters (Elwell et al 2002a; Elwell et al., 2002b). In general, the OSU team has shown that, at the aeration rates typically employed for composting, a greater level of aeration leads to faster destruction of anaerobic compounds.

However, the greater aeration also produces a greater release of odorous compounds into the environment due to the increased air flow through the pile. Thus, odors tend to be reduced by strategies that minimize aeration (within limits), such as a lower air flow rate and/or intermittent rather than continuous fan operation. The OSU research demonstrates that *over aerating* a pile increases odor emissions. Thus, after the process oxygen and temperature needs are met, aeration should be kept to a minimum. Although odorous compounds may persist longer, only small amounts escape into the surroundings.

Containment

A lot can happen to an odorant molecule before it becomes an “emission.” Most odorants are intermediate compounds that contain energy and nutrients that microorganisms can use under the right conditions, and if time avails. Therefore, given time and the right conditions, most odorants can be decomposed within the mass of materials in which they are formed.

The vast majority of potential odorants that form likely meet this fate. It is in the interest of a composter to slow the escape of odorants, retaining them within the pile as long as possible, thereby giving the microorganisms time to further decompose the molecules of odorants. This situation not only minimizes the emissions of odors, it also conserves nutrients within the compost. There are two primary means of retaining volatile odorant molecules – (1) capturing them on their way out via adsorption and absorbtion; adsorption and (2) blocking their escape with covers.

Adsorption and absorption

Unless it is formed at the pile surface, or physically transported to (e.g. turning), a given odorant molecule faces a tortuous path to liberation into the ambient environment. In that path there are road blocks in the form of particle surfaces (adsorption) and pools of moisture (absorption) that can attract molecules via electrostatic or chemical forces. Once trapped or delayed on particle surfaces or in moisture, the odorant molecules are subject to decomposition.

On a molecular scale, organic materials have large internal surface areas that are good for adsorbing molecules. Various electrochemical mechanisms work to attract molecules to these surfaces. While many composting feedstocks, and compost itself, are good adsorbents, it can be an advantage to include materials that are especially effective adsorbents. Activated carbon is well known for this quality. Others include peat moss, wood ash, coal ash and finished compost. Ash that retains more organic carbon is more effective than ash that is completely combusted (BioCycle 2004). Highly adsorbent inorganic materials, like zeolite, have also been investigated for this purpose.

Numerous researchers have investigated including adsorbent organic materials into the feedstock mix as amendments for the purpose of odor control. Examples include peat moss (Mathur et al, 1990), wood ash (Rosenfeld and Suffet, 2003), coal ash (Das, 2000) and compost (Buyuksonmez et al., 2006) Often, the adsorbent provides other qualities in addition to the adsorbing surfaces.

For example, peat moss lowers the pH, wood ash increases pH and finished compost provides a diverse pool of microorganisms. In general, the research demonstrates a noticeable reduction in odor emissions due to these amendments. Their value and utility depends on the feedstocks, how critical odor control is and other economic factors like the cost of the amendments. While it is not the norm, compost and wood ash are used in practice as odor-reducing amendments. (BioCycle, 2004)

Moisture is critically important for the composting process but it also plays a role in retaining volatile compounds. Many volatile compounds, like ammonia, exist in equilibrium with soluble forms, like ammonium. As the amount of moisture decreases, soluble forms are converted into volatile forms, which are subject to escape. In addition, the pools of moisture provide hospice for the microorganisms working to decompose the odorants. In short, there are many reasons not to let composting materials become dry just as they should not become too wet.

Covers

Odorous compounds escape from the exposed surfaces of piles, windrows and bins. This condition holds even for forced aeration systems (and also to some extent for negatively aerated piles and bins). One approach is to block or hinder the escape of odors by covering the exposed surfaces. In doing so, the odorants remain within the composting mass and eventually decompose. Of course, because composting relies on the exchange of air with the ambient environment, the covers must be somewhat permeable to air or oxygen.

The primary way that covers are used in practice is by applying a somewhat porous material to the exterior surface. Typically, the material used is a relatively porous amendment like wood chips, woody screen overs or chipped brushy green waste. Less porous materials like compost, sawdust and straw are also used. In these cases, the cover materials physically hinder the path of the escaping odorants.

However, they also, and perhaps more importantly, serve as adsorbents that remove the volatile compounds from the exiting air stream. In a sense they serve as pseudo-biofilters. Wood chips have long been used for this purpose in composting biosolids (Rynk, 1992). Compost also is as a cover at facilities because it is readily available and because it is an excellent adsorbent and medium for decomposition. In research associated with this C-CORP project, Buyuksonmez et al. (2006) found compost covers to be an effective measure for reducing odor emissions.

In addition to porous covers of organic amendments, synthetic membrane covers are also used to contain odorants within piles and windrows. In the past ten years, several innovative woven fabric membrane materials have been introduced that are relatively permeable to air and oxygen but impermeable to moisture and molecules of larger molecular weight. These membranes simply block the movement of many volatile molecules. Much of their effectiveness occurs because moisture tends to condense on the underside of the membranes. The moisture helps to trap and absorb odorant molecules. When the moisture drips back onto the pile below, it returns the odorant molecules back into the composting process.

Enclosures

Once odorants leave the surface of an open windrow, pile, bin or other surface (e.g. pond, puddle, tainted soil), their fates are subject to the whims of the natural environment (e.g. weather, geography, atmospheric chemistry). Those whims can deliver the odorants to unwelcoming neighbors. However, composting facilities have another line of defense—enclosures. Enclosures include building, composting reactors and vessels, containers and other envelopes that isolate the composting system from the surroundings. Enclosures differ from covers in that the emissions are not retained within the composting system but captured and contained by the facility. Typically, the air within the entire enclosure (e.g. building) is captured and then treated in a biofilter or other treatment device. Another approach is simply exhausting the captured air after diluting it with copious volumes of outside.

A building may enclose an entire facility (Accortt et al, 2001) or just the most odor-critical components of the facility (e.g. receiving and mixing areas, first stage of composting). Other options include aerated containers and aerated plastic bags or pods, Enclosures are an expensive but potentially effective means of odor control. They do not eliminate odors altogether but through engineering and design, make odor management more controllable. Most passive odor emissions and area sources either become point sources (e.g. building exhaust) or are transferred to a single area source like a biofilter that can be more actively managed.

Odor Treatment—Biofilters *et al.*

As already stated, odor emissions can be captured through enclosures or negative aeration. Once captured, a number of treatment alternatives can be used to greatly reduce the amount of odorous compounds released into the environment. Options include biofilters, soil filters, chemical scrubbing, thermal oxidation and, more recently, non-thermal plasma oxidation.

The composting industry has primarily adopted biofiltration as its favored odor treatment technology. In part, the appeal of biofiltration is that it is similar to composting itself. Like a composting pile, biofilters require management and attention to nutrients, moisture, microbiology, porosity and aeration. Biofilters can go bad and become a source of odors.

However, biofilters can be a prominent source even when they are working correctly because all other odor emissions tend to be funneled there. When facilities are completely enclosed, the outside biofilter can be the primary source of potential odors at the site. Again, this situation does not imply that the biofilters are ineffective, just that they need to be managed and remain a source that deserves attention. Biofilters have a large surface area, usually open to the outside environment. They constitute an area odor source and should be modeled and managed as such. Many excellent references discuss the design, operation, management and performance of biofilters including Kuter, 1990, Haug, 1993, Wililams and Miller, 1993, Epstein, 1997, Das, 2000, Michel et al., 2002, and BioCycle, 2004.

Other treatment devices have found application at composting sites and other facilities that generate odors from organic materials (e.g. wastewater treatment plants). Scrubbers that employ chemicals to react with and neutralize odorants have been installed at several of the larger composting facilities (Haug, 1993). Often, they are preferred where a specific compound requires treatment (e.g. ammonia or hydrogen sulfide). Non-thermal plasma technology has been recently introduced. It employs electrical energy to generate free radical ions that react quickly with many odorous compounds. This approach is promising because it can be adapted for a smaller scale (Paul, 2006).

Transport and Fate in the Environment

Odor emissions *at* composting facilities are not particularly worrisome. The critical worry is odors *beyond* the composting facility, and primarily only when the odors reach people who object to them. Of course, the two issues are related, linked by the transport of odorous compounds to sensitive receptors and their fate in the environment beyond the boundaries of the composting facility.

Most volatile compounds released into the atmosphere are eventually "eliminated" by chemical reactions within the atmosphere and/or fall to the earth with precipitation and other forms of atmospheric deposition. However, much more quickly, they mix with, and become diluted by, the air within the atmosphere. The latter phenomenon—dilution—is how emitted odors practically "disappear."

While the mixing and dilution is taking place, an intact "plume" of odorous air can be transported beyond the sources of the odors to neighbors. At that point, if the mixing has not diluted concentrations below human detection limits, the odors can impact the surrounding community. How quickly the odors are diluted depends on atmospheric conditions, especially wind and temperature, which in turn determine the stability, or conversely the turbulence, of the atmosphere and thus the degree of mixing. Topography and the landscape also play a role. All of these factors also influence *where* the odors travel. The proximity of neighbors is a very important factor in determining whether or not an impact occurs.

Transport Patterns—of Plumes and Puffs

When odorous compounds, or any other pollutants, are released into the air, the surrounding air effectively assimilates these compounds. Although it is an oversimplification, it can be said that the odors do not move independently from the air but travel within the assimilating air parcels and only gradually diffuse, decompose or wash out. In a sense, a moving parcel of air retains its identity (and embedded odors) but its character erodes over time and distance. How quickly that erosion takes place depends on the presence and strength of the forces that tend to diffuse, dilute, disperse and chemically alter the compounds within the air. With little wind or other disturbing forces, the air travels intact for some distance while progressively mixing into the surrounding ambient air.

In air pollution terms, this intact but eroding contaminated air stream is called a *plume*. It is well represented by the vapor plume from the exhaust stack of a power plant. The plume from the stack trails on for a distance, spreads out and eventually disappears. The wind, atmospheric temperature profile and also the surrounding landscape determine the plume's direction, shape and longevity. If the plume remains warmer than the surrounding air, the plume continues to rise. While exhaust from a stack typifies a plume, area sources of odors can also be considered to travel and disperse in relatively intact plumes. An area source can be treated as a plume that has already spread to the width of the area source (Lui, 1997).

Plumes break apart by the action of a combination of diffusion, wind and rising air currents. Because wind and air currents change constantly and instantaneous so do the plumes. However, under relatively calm conditions, and on average, the plumes tend to gradually disperse, principally by diffusion (de Nevers, 2000). The diffusion causes the plume to spread out along its length. It spreads horizontally and vertically. At any instant in time the plume is actually twisted in a disorderly shape by random turbulence (de Nevers, 2000). However, the spreading pattern represents the net effect over time—and can be considered a steady state.

The way in which a plume spreads—its spreading shape—is commonly described by a mathematical relationship know as a Gaussian distribution. The Gaussian distribution is the familiar "bell shaped" curve that widens symmetrically around a centerline. When applied to plume spreading, the curve is turned on its side with the point of the bell at the odor source (e.g. stack outlet) and the curve spreads horizontally and vertical, although not necessarily in the same way. To predict how a plume will behave, air pollution professionals use mathematical equations that define the plume's Gaussian spreading pattern. The spreading pattern in turn correlates with the movement, concentrations and dispersal of pollutants within the plume. The equations are used in computer models (e.g. the Gaussian model) to predict pollutant concentrations, like odor, at various directions and distances from the source.

A plume is an idealized way to envision odor emissions. It represents a continuous stream of emissions at a constant strength and rate. However, odors are rarely emitted as a continuous stream at composting sites. The strength of the concentrations of odors compounds change and their rate varies. A good example would be the odors emitted upon turning.

In such situations, the plume model does not work well. It also does not work well when the air does not disperse in the normal plume-like fashion that is spreading uniformly in a single direction. For instance, under very stable atmospheric conditions (e.g. temperature inversions, see below), the odorous air may hardly disperse at all (Haug, p 607). In these cases, odor emissions are sometimes modeled as a series of discrete puffs – a brief burst of odor release. Each puff can differ in odor concentration and character, although many computer models assume each puff is the same odor concentration (Brant and Elliott, 2004).

Proximity

The proximity of neighbors (distance and direction) to an odor source is a huge influence in odor impacts. It determines whether there is sufficient distance (or time) available, in nearly all situations, to dilute the odors below the detection limits. The number of odor incidents that neighbors are willing to forgive is usually small, so the distance must be large enough for odor to effectively disperse under all but the worst case conditions. There is nothing more effective at preventing odor problems than an isolated site—a long distance from the nearest neighbors (Miner, 1995). The next best situation is a long distance to neighbors in the direction that odors usually to migrate. However, since wind and weather conditions at any site usually vary, there is rarely a "safe" direction.

Publications offering composting guidance and regulations have specified minimum buffer distances between the boundaries of a composting facility and the nearest residential or commercial neighbors. Such recommended or specific minimum buffer distances range from 150 ft. to over 500 ft. (Epstein, 1997). The basis for these recommendations is not clear in most cases. They may develop from odor modeling, guidance in earlier publications or round numbers that represent practical best guesses. Overtime, the recommended minimum distances have tended to increase as the neighbors located at further distances have lodged complaints.

For general situations, it is impractical to establish a buffer distance that will eliminate all odor complaints. Odors have been known to travel a few miles in large enough concentrations to elicit complaints. Buffer distances of multiple miles are impractical for most composting facilities because workable remote sites are few (or few remain remote).

The most reasonable approach is to set a practical distance that limits the odor impacts to a minimal number per year. For specific facilities in specific locations, odor modeling can be used to predict the number of impacts on neighbors. However, it must be emphasized that the nature, topography and management of the specific facility, plus the attitude and expectation of neighbors, determine the frequency and distance of odor complaints. Some composting facilities operate successfully within a few city blocks of residential neighborhoods. Some facilities in seemingly remote locations have been plagued by odor complaints from neighbors miles away. In summary, although setting a minimum buffer distance provides some degree of protection from odor impacts, it is very difficult to establish a good general standard. Furthermore, meeting recommended buffer distances will not in itself eliminate odor impacts nor guarantee that odors won't impact neighbors beyond the buffer distance.

Urban Encroachment

In numerous cases, composting facilities that were initially sited in well-buffered, seemingly isolated locations eventually had to struggle with odor complaints (Rynk, 2003a, 2003b). The incessant march of urban and suburban development has impacted farms, factories and composting facilities alike. In some cases, the encroaching development has forced composting operations to manage better or upgrade technology to minimize odor impacts on developing communities. In other cases, the changing landscape has led to facility closures. The "Preliminary Odor Assessment" component of the C-CORP project found encroachment to be a major factor, if not the major factor, in the odor problems plaguing the ten facilities examined by the preliminary assessment. Four of these ten facilities have closed.

A long distance to neighbors continues to be the best defense against impacting the community. However, since land is expensive to purchase as buffer space, and undeveloped space continues to disappear, composters and community planners need to find other ways to preserve odor-generating facilities in the light of encroaching development.

In addition to tighter facility management, better technology and best management practices, communities can look to creative zoning practices and community education to make sure that citizens are aware of the presence of the composting facility, its operation and its potential to occasionally impact the community with odors. Establishing an understanding of the facility and its operation plus realistic expectations of its odor performance are important steps (Goldstein, 2006).

The burden of public relations should fall on both the community leaders and the composting facility. However, the personal experiences of the authors suggest that communities are at best slow to take on this task, and more often reluctant to do so. Therefore, the composting facility should enlist, but not wait for, the support of local communities and the regulatory agencies (Goldstein, 2006.)

Wind

Wind has a dual effect. Wind carries odor-laden air from the odor sources to the neighbors. It also disperses and dilutes odors within the atmosphere. The speed, direction and consistency of the wind influence odor impact. The worst case is a slight wind (e.g. 2 to 5 mph) in the direction toward the most sensitive neighbors such that odors are continually carried to the neighbors with little dilution.

The best case is a strong turbulent wind (e.g. >10 mph) that frequently changes direction, which disperses the odor and causes only fleeting impacts, if any. In general, a brisk wind is usually good; that is, it usually helps to avoid odor impacts by diluting odor emissions. However, the specifics of the site and situation determine whether that statement holds true.

In general, wind direction and speed are influenced by the following factors, in order of their influence (de Nevers, 2000):

1. Storms and weather fronts: The relative proximity and difference between high- and low- pressure centers primarily determine wind directions and speed, over and above other factors.
2. Land features, including mountains valleys and canyons: In absence of overriding influences from storms and weather fronts, winds tend to follow valleys and canyons and locally blow up and down mountain slopes as the land surface heats and cools. In these situations, the wind typically reverses direction from morning to night, and between cold and warm seasons. The effect is greater with deeper or steeper features.
3. Onshore and Offshore breezes: When other effects are small, winds blow on- and off-shore of water bodies, with the direction depending on the relative temperatures of the land and water. When the water body is cooler (summer and/or afternoons) the breeze blows onshore (replacing warm air over the land that has heated and risen). When the land surface is cooler (winter and/or at night), offshore breezes occur.
4. General wind patterns: When the other effects are not present, winds tend to be light and follow the dominant wind patterns on the earth's surface due to general atmospheric air circulation (e.g. trade winds, westerly's).

Guidance for siting composting facilities routinely advises composters to consider prevailing wind direction. The guidance states that it is best to avoid situations where the prevailing winds blow toward neighbors. This advice is sound and prudent but it can be difficult to implement in practice. Because a facility can have neighbors in all directions, the guidance should state that prevailing winds should not blow toward the most sensitive neighbors.

Secondly, urban/suburban expansion has a way of filling in the vacant spaces around a facility with sensitive neighbors. Thirdly, prevailing wind direction is the direction that winds blow most often. It says nothing about wind speed or how frequently the wind blows in the prevailing direction. In fact, the wind blows in the "prevailing" direction only a percentage of the time, and typically less than 25% of the time (Natural Resources Conservation Service, 2006), especially if NNW and WNW are considered different than NW). In short, prevailing wind direction is an important factor but a favorable prevailing wind does not in itself preclude odor impacts on neighbors in other directions.

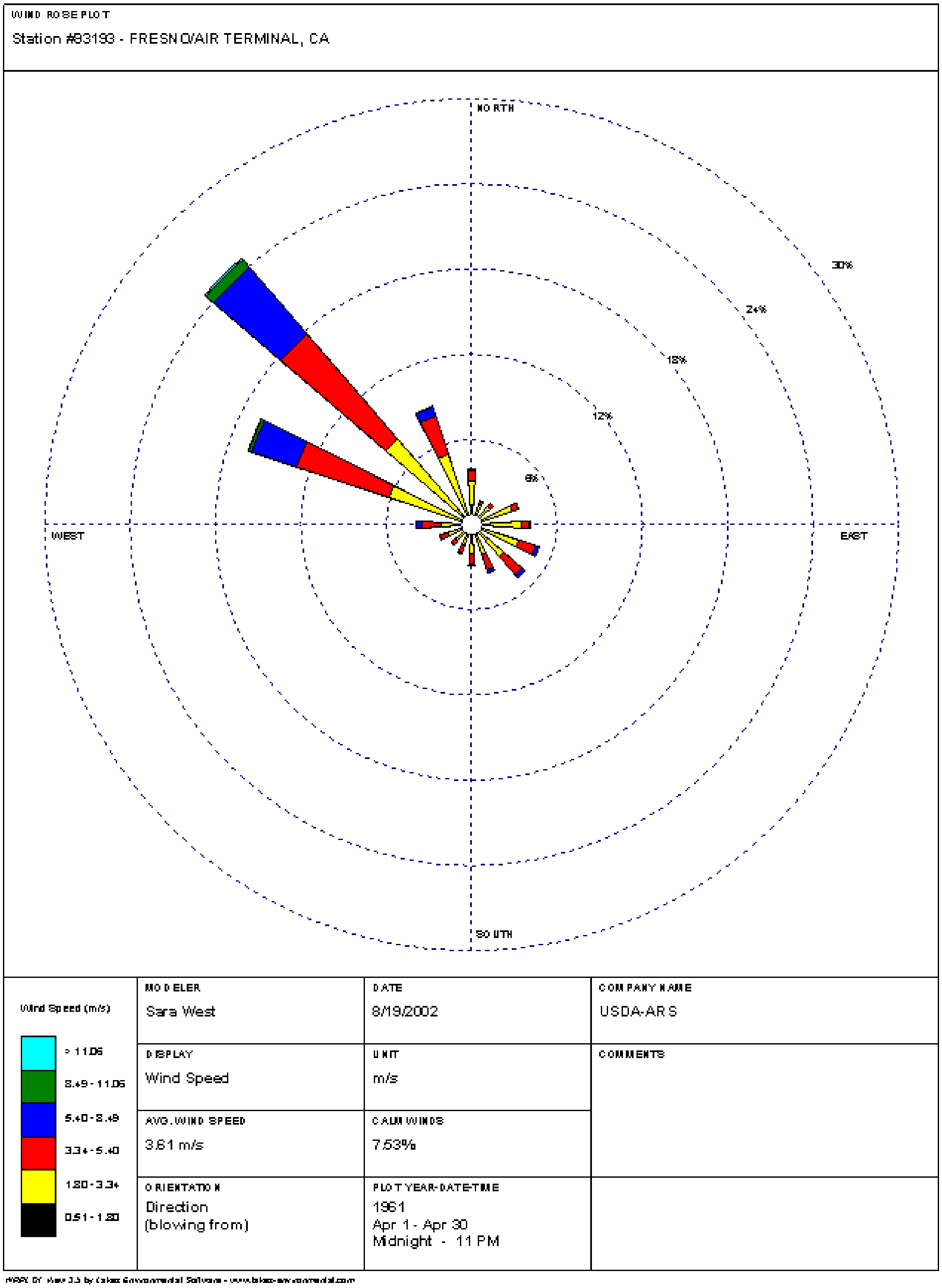
The direction of prevailing winds is largely determined by local topography including valleys and canyons, mountains and large water bodies (e.g. lakes, oceans). Where these features exist, the prevailing winds are more prominent and predictable. Where they are absent, such as on broad inland plains, wind direction tends to be more variable. For a given location, prevailing wind direction, and wind direction patterns generally, can be ascertained from wind data collected at nearby weather stations. Such data is usually available from the federal and state public agencies that regularly collect weather data.

Wind roses are particularly helpful in evaluating the wind characteristics of a given location. An example wind rose is shown in Figure 2 (Natural Resources Conservation Service. The wind rose is a circular graph with 16 wind direction divisions. The spokes of the graph show the frequency (i.e. percent of the time) that the wind is blowing *from* the direction indicated by the strokes. The spokes emanating from the center of the wind rose correspond to the frequency of the winds in that direction. (The wind direction identifies the direction that the wind is coming from. Hence, a west wind is blowing from the west and towards the east)

Many wind roses, including the one in Figure 2, also present information about the distribution of wind speed at the location. Usually the wind speed range is indicated by the color and/or thickness of the corresponding section of the spoke. The length of a wind speed section indicates the frequency that a particular range of wind speed occurred in the direction of the spoke. Wind roses provide a good visual representation of the wind characteristics of a given location. Wind roses for many weather stations can be obtained from: http://www.wcc.nrcs.usda.gov/climate/windrose.html (Natural Resources Conservation Service, 2006).

One problem with using wind roses is that they are developed from data collected at weather stations. Wind characteristics can vary greatly among specific sites, even sites that are relatively close together (e.g. within a mile). The differences can be due to landscape features, buildings, topography and simply local variations in the weather conditions. For this reason, it is helpful to have a weather station on the composting site, especially if odor impacts are a concern, and more so if the odor impacts are disputable. Wind roses and other weather data from nearby weather stations remain good resources for planning, managing and troubleshooting composting sites.

Figure 2: Example of wind rose for a specific location and time of year (Fresno, April).



WIND ROSE PLOT
Station #93193 - FRESNO/AIR TERMINAL, CA

MODELER: Sara West
DATE: 8/19/2002
COMPANY NAME: USDA-ARS
DISPLAY: Wind Speed
UNIT: m/s
COMMENTS:
AVG. WIND SPEED: 3.61 m/s
CALM WINDS: 7.53%
ORIENTATION: Direction (blowing from)
PLOT YEAR-DATE-TIME: 1961 Apr 1 - Apr 30 Midnight - 11 PM

Source: http://www.wcc.nrcs.usda.gov/climate/windrose.html (Natural Resources Conservation Service, 2006.)

Atmospheric stability

Winds generally mix the atmosphere near the earth's surface in the horizontal plane—east, west, north and south. Vertical mixing also occurs, from rising and falling air. The atmosphere is considered *unstable* when conditions are such that vertical mixing readily takes place. When conditions hinder vertical mixing, the atmosphere is *stable*. Vertical mixing is good for composting facilities because the plume of odors is carried upwards, where it is very unlikely to encounter an objecting human nose. When it rises, it is also likely to be diluted and dispersed by the more vigorous winds aloft.

In the lower atmosphere, up to about 6,000 ft. above the ground, vertical air movement occurs because of temperature differences at different altitudes (de Nevers, 2000). The vertical temperature profile, that is the change in temperature with altitude, is referred to as the *lapse rate*. When it refers to the actual temperature gradient of the ambient atmosphere, it is also called the *ambient lapse rate* (Lui, 1997).

"Normally," the air temperature decreases moving from the ground upward (technically, the lapse rate is said to be positive when the temperature decreases with increasing altitude). When air near the earth's surface is heated by the sun's energy, it becomes less dense, and therefore buoyant, compared to the cooler air above. The warm air rises and the cool air falls, creating vertical mixing. However, if the air near the ground (e.g. at the composting facility) is cooler than the air aloft, it does not rise and no vertical mixing occurs. Conditions routinely arise that cause the atmosphere to increase in temperature with altitude. This situation is known as a temperature inversion (i.e. negative lapse rate).

In fact, the situation is more complicated than this description. Vertical air movement can be prevented even when inversions are not present. Because air expands and subsequently cools as it rises, the vertical movement of air also depends on its rate of cooling relative to the temperature of the surrounding air. As air rises, it expands and cools at a constant rate. If the assumption is made that the air loses no moisture as it rises, and thus no energy is lost or gained, then the air decreases in temperature at a predicable rate, known as the *adiabatic lapse rate* (de Nevers, 2000).

When the air remains unsaturated, the *dry* adiabatic lapse rate applies and air temperature decreases by 5.4°F per 1000 ft. (10°C per km) of elevation gain. Air that becomes saturated follows a different and lower lapse rate – the *moist* adiabatic lapse rate, which can vary approximately between 4 and 6.5°C/km (Lui, 1997; de Nevers, 2000). A given parcel of air is likely cool at a rate between the dry and moist adiabatic lapse rates because of the moisture it contains (and loses) and varying air pressures but the dry adiabatic lapse rate provides a reasonable approximation.

In order for a parcel of air to rise, it must be *more* than just warmer than the parcel of air above it. The rising parcel must *remain* warmer than the surrounding air along the way up. This condition depends on the rising air parcel's lapse rate (e.g. 5.6°F/1000 ft.) and the vertical temperature profile—that is, the ambient lapse rate of the surrounding air. If the vertical temperatures of the surrounding air do not fall as fast as the rising air's lapse rate, than vertical mixing stops. This situation can happen even when the air temperature decreases with height. A temperature inversion is just an extreme case.

This phenomenon is better explained by Figure 3. The figure shows the adiabatic lapse rate that a rising parcel of air tends to follow plus the ambient lapse rates for three different atmospheric conditions. Again, the ambient lapse rate is simply the vertical temperature profile of the air. The two temperature profiles to the right of the adiabatic lapse rate (dotted line) are stable conditions in which no vertical mixing would occur. The far right profile is a temperature inversion. The temperature profile to the left of the adiabatic lapse rate is unstable and conducive to vertical mixing. In the unstable case, the rising air remains warmer than the surrounding air because the adiabatic lapse rate is less than the ambient lapse rate.

The lapse rate of a rising parcel of air is essentially fixed and approximately equal to the adiabatic lapse rate. Therefore, it is the ambient lapse rate that determines the stability (i.e. vertical mixing) of the atmosphere at any time. The ambient lapse rate is largely determined by wind, sunlight, radiational cooling at night and cloud cover. Using these meteorological conditions, atmospheric stability classes have been established (Table 6). Composting facilities should hope for conditions that create more atmospheric instability (e.g. A, B), which encourage dispersion of odors. Haug (1993) mentions that the stability categories are more applicable to open and rural areas. Trees, urban "heat islands" and rough terrain tend to confound the conditions. Also it is interesting to note that increasing wind speed tends make the atmosphere more stable during the day but less stable at night.

Figure 3: Ambient lapse rates for three different atmospheric conditions

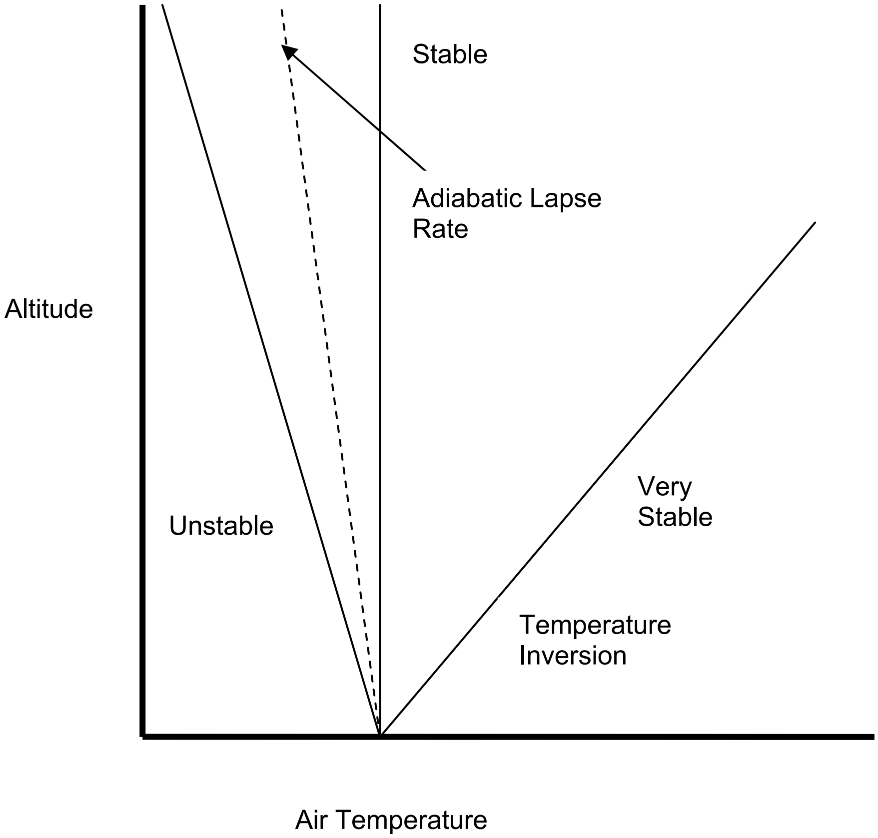


Table 6: Atmospheric stability categories

		Day		Night	
Surface Wind Speed	Incoming	Solar	Radiation	CloudCover1	
_ (m/s)	Strong	Moderate	Slight	≥4/8 Low Cover	≤3/8 Cover
<2	A	A - B	B	--	--
3-Feb	A - B	B	C	E	F
5-Mar	B	B – C	C	D	E
5 – 6	C	C - D	D	D	D
>6	C	D	D	D	D

A = extremely unstable

B = moderately unstable;

C = slightly unstable;

D = neutral;

E = slightly stable

F = moderately stable

Assume neutral condition D for all overcast conditions, day and night

Source: adapted from Haug, 1993

Temperature Inversions–Diurnal Patterns, Other Factors

A temperature inversion is the condition when warm air sits above a layer of cooler air. Temperature inversions are not welcome occurrences for composting facilities. They prevent air from rising, dampen vertical mixing and keep potentially odor-laden air near the ground. The odor-laden air may then travel at ground level to neighbors, carried by light winds or air drainage (see following sections).

An inversion can take place through the entire profile of the lower atmosphere as shown in Figure 3, or only to a certain height, as depicted in Figure 4 below. In any case, the warm air aloft prevents vertical air movement and keeps the air near the ground from moving and mixing upwards. Odorous air remains near ground level and either accumulates a the site and/or migrates off site at “neighbor-level.” Temperature inversions are often correlated with numerous odor complaints and severe odor complaints (Haug, 1993). Therefore, composting facilities should recognize and anticipate the conditions that lead to inversions.

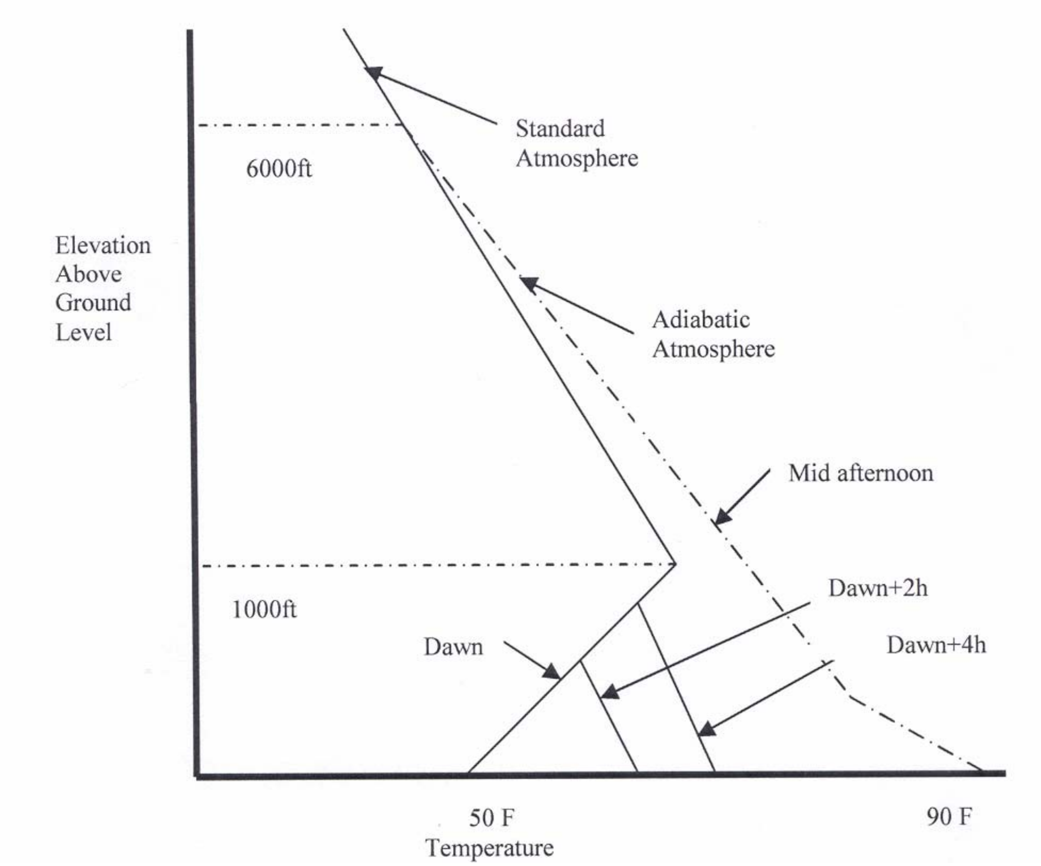
Air temperatures are not constant so Figure 3 represents a snapshot of conditions at one point in time, and a simplified snapshot at that. Atmospheric temperature profiles and stability conditions change—with daytime solar heating, nighttime cooling, winds and weather fronts. Temperature inversions come and go.

Among the more predicable patterns of change are those that evolve through the cycle of a day. These can result in stable conditions during some parts of a day and unstable conditions during other parts. Typically, radiational cooling of the earth's surface on a clear night lowers the air temperature near the surface while the air above remains warmer (because, compared to the earth, air is a poor radiator of heat, and also a poor absorber of it).

A temperature inversion develops during the night, at least in the lower levels of the atmosphere, as shown in Figure 4. After sunrise on a clear day, solar radiation begins to warm the earth and the air temperature near the surface increases. As the morning lengthens, the air temperatures near the ground increase and the temperature inversion breaks up the lower layer, although an inversion persists at higher elevations. By afternoon, the inversion is gone and a "normal" unstable temperature profile develops, generally matching the adiabatic lapse rate. Near sunset, the ground and the air around it begins to cool and a temperature inversion may reestablish itself near the ground and grow stronger and higher through the night. Clouds, winds and changing weather are among the factors that moderate the changes that work to establish and disperse temperature inversions.

The diurnal patterns described above help to explain why many composting facilities receive more odor complaints in the early morning and early evening. The low level temperature inversions at the beginning and end of the day, combined with typically low winds during these periods, hinder mixing and dispersion at ground level.

Figure 4: Vertical temperature distribution at various times on a cloudless day with low or average winds in a dry climate



Source: adapted from de Nevers, 2000

Air Drainage

An air mass is subject to gravity. Thus, if left undisturbed, air follows the same drainage patterns as water (Brant and Elliot, 2004). As cool air displaces less dense warm air, it flows down slopes and into valleys and along stream and water channels just as water does. Wind and vertical turbulence mix the air and overwhelm the tendency of air to drain downhill. However, if winds are light, cool air tends to follow the “lay of the land” and collect in low spots. The draining air carries with it whatever odorous compounds are embedded. As described above clear nights tend to be accompanied by diurnal temperature inversions, which dampen vertical air movement. Furthermore, winds tend to be lower during the night, setting the stage for air drainage.

Air drainage occurs when the air near the earth’s surface cools due to nighttime radiational cooling of the earth. If the air at higher elevations cools more than at lower elevations, the air flows down the slope. Only a slight slope is necessary. Cooling occurs faster in wide-open expanses with a clear “view” of a cloudless night sky. In contrast, areas cool less rapidly at night when shielded from the sky by trees, steep slopes, canyon walls or buildings. In a given region, these radiation-blocking elements may be more common to lower elevations. Furthermore, in developed areas, the ground, and adjacent air remain warmer due to the heat retained by the thermal mass of the developed landscape (e.g. asphalt parking lots, concrete buildings). Because development normally occurs first in valleys and along waterways, on clear nights cooler air from uphill and less developed areas readily drains into the developed areas, displacing the warmer air down slope. Note that when an open area warms faster than its surroundings on sunny days, the direction of the air flow reverses from the cooling phase. However, there are many complicating factors at work, including cloud cover (often greater over higher elevations) and the more intensive daytime heating and greater temperature rise that occurs in developed areas.

A composting site is typically an expansive area of cleared land, open to radiational cooling. While not all composting sites are located uphill of development, those that are may discover that early-morning odor complaints come from downhill neighbors after clear relatively calm nights. Neighbors, located in a nearby low spot, or bowl, are most susceptible if winds are not active. If possible, it is wise to avoid siting a facility that is located in a natural air drainage "channel." As described in the next section, physical barriers and a rough and changing topography help to disturb air drainage patterns by offering resistance to the air movement and increasing turbulence and dispersal of odors.

Topography

Topography is determined by natural features and man-made ones. Natural features include hills, mountains, valleys, water bodies, trees and vegetation, undulating surfaces and simply sloping ground. Manmade features include buildings, roads, bridges, fences, powerlines and planted landscapes.

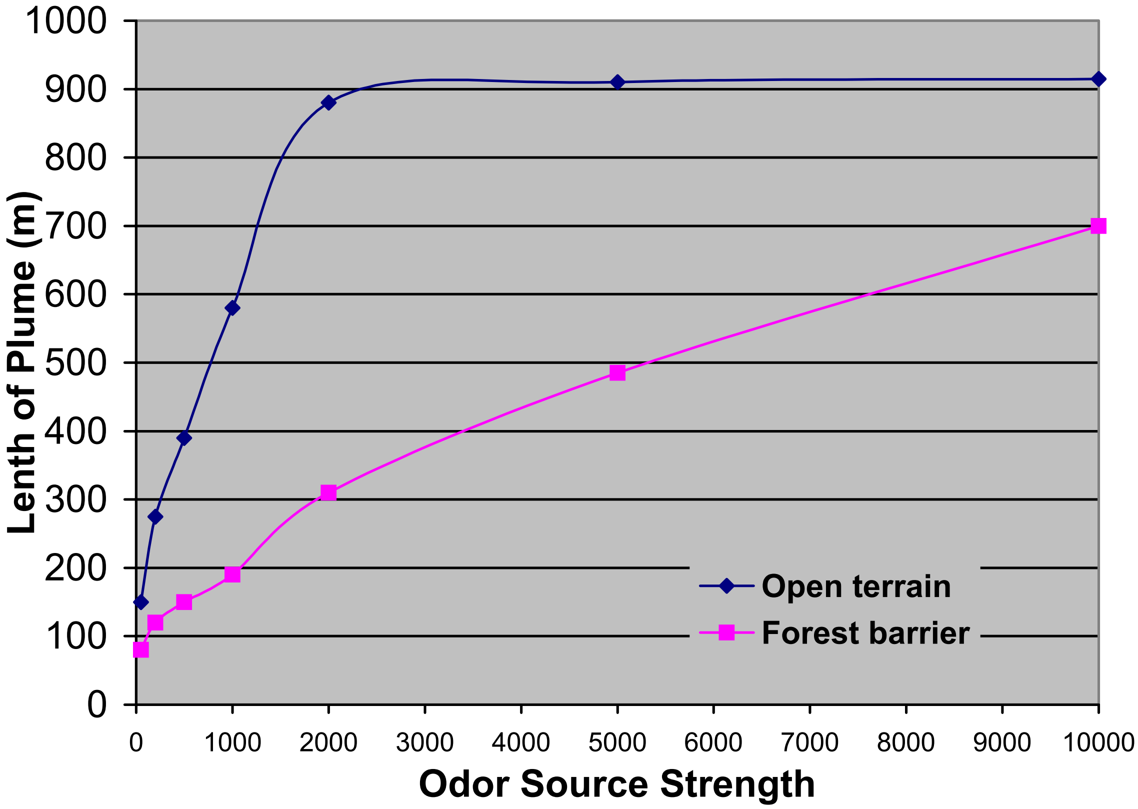
The topography can greatly affect air movement in a number of respects. The topography may provide barriers to air flow and slowing winds (e.g. wind breaks), establish airflow channels (e.g. valleys), increase turbulence (e.g. trees) and generally creating local –scale air circulation patterns (Lui et al., 1997). For a composting facility, desiring to minimize off-site impacts, the effect of topography can be negative or positive. The effects are negative when the topography directs air flow from the facility to sensitive neighbors before the odorants in the air are effectively dispersed. The effects are positive the predominant local air patterns are directed away from neighbors and when the topography hinders air movement and creates turbulence, which enhances dispersal.

A facility can use latter effects to its advantage. For example, retaining a row of trees around the site can interfere with air drainage and create turbulent eddies when the wind is blowing. Where trees do not exist, a soil berm, tall fence or hedge can have a similar but lesser effect, and fast-growing tree species can be planted for the longer term. In addition to the enhanced turbulence and odor dispersal, trees, fences or soils berms along the perimeter provide a visible barrier that shields the facility from the public, and vice-versa.

Figure 5 illustrates the effect of a forest stand on the concentration of an odor plume with distance. The figure was generated by computer simulation under assumed conditions (Chastain and Wolnak, 2000). It shows the distance required to dilute at a plume of odorous air to 1 *odor unit* (OU) from odor sources of various strength (an odor unit is a measure of the strength of an odor, see following section for additional description). For instance, assuming a source is emitting odorous air at a strength of 2000 ou, Figure 5 shows that the plume requires about 3000 ft. (900 m) of open terrain to decrease to 1 ou. However with a forested barrier, the plume reaches 1 ou in less than 1000 ft. (300 m).

The forested boundary clearly reduces the chance that a neighbor will be impacted under the conditions assumed.

Figure 5: Effect of terrain on length of odor plume at various odor strengths



Source: adapted from Chastain and Wolak, 2000.

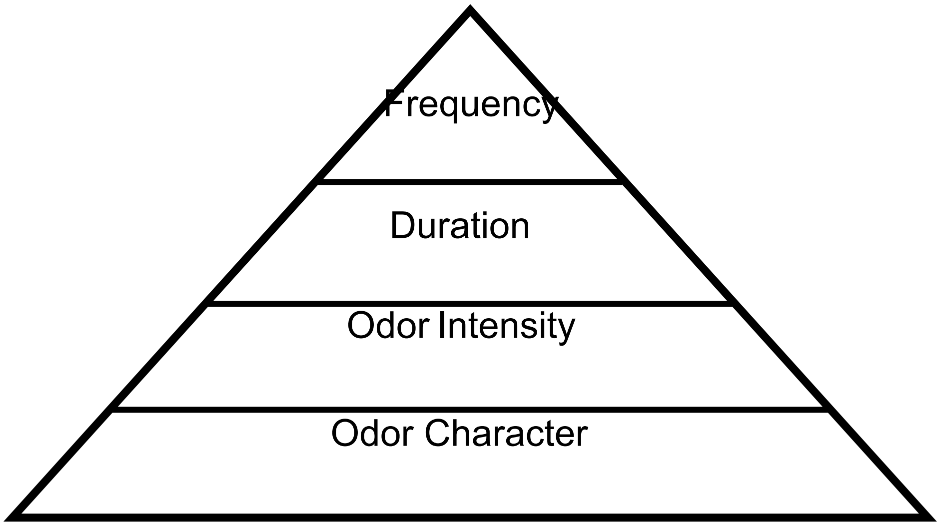
What Determines the Severity of Off-Site Impacts?

Potential odor impacts are influenced first by conditions surrounding the site – conditions that affect the transport and fate of odorous compounds in the conveying air plume (e.g. weather, topography, distance to neighbors). However, an odor will not endure beyond the facility, unless there is a discerning person in the path of the air plume. The discerning person must first detect the odor, then find it objectionable and become sufficiently annoyed to react negatively. This chain of events depends on the attributes of both the odor episode and the discerning individual.

Dalton (2003b) uses the acronym FIDO to represent the factors that determine the severity associated with an odor episode. FIDO stands for *frequency*, *intensity*, *duration* and *offensiveness*. The latter factor, offensiveness is where the human factor enters. McGinley et al. (2000) depict the same factors as a pyramid (Figure 6) substituting “odor character” for offensiveness.

If the odor dissipates relatively quickly and doesn't return, then the odor has no effect, in most cases. However, if it remains long enough to be bothersome or reoccurs repeatedly, then odor complaints are likely, either with the present odor occurrence or the next one. The severity and the force of the odor complaint depends a great deal on the person sensing the odor – his or her sensitivity, expectations, understanding of the situation and the health risks, feelings about composting and history, especially his or her history with the facility. These psychological and social factors are important determinants of whether or not a nuisance odor passes without controversy or becomes a problem. In fact, the expectations and attitudes of people can lead to odor complaints when the odors are fleeting, and even in the absence of odorous compounds.

Figure 6. Citizen Complaint Pyramid



Source: McGinley et al., 2000.

Detection—Attributes of the Odor Episode

For an individual to detect an odor, an odorant (or mix of odorants) must be present in a high enough concentration for the individual to detect the resulting odor. That condition is necessary but not sufficient to yield an odor complaint. To reach the complaint level, the odor also must be sufficiently annoying, which is largely determined by its intensity and quality.

Furthermore, the odor must persist, either continually for an uncomfortable duration of time or repeatedly for even short periods. Brief and occasional odor episodes are usually excused. Finally, the timing of the incident is a factor. A neighbor will have little tolerance for odor incidents that occur during a June graduation picnic. The sensitivities, expectations and attitudes of the discerning individual influence whether or not these conditions combine to yield an odor complaint, and how forceful that complaint is (see following section).

Concentration

Certainly, the concentrations of odorants in the air decrease as the travels from the source. Composting facilities rely on and hope for atmospheric mixing and brisk winds in the right direction to odorants that might leave the site. However, if the atmospheric and geographic conditions do not disperse the odorants enough when the air plume reaches the site boundary, the odor might be detected by a potentially-objecting person (sometimes called the "receptor"). The actual pollution concentration, in ppm, at which an odor is detected (i.e. the detection threshold) varies with the nature of the odorants, as shown earlier in Table 1. Furthermore, individuals vary in their sensitivities so the detection thresholds represent the average person.

As described earlier, the concentration at which an individual recognizes an odor is usually two to ten times higher than the detection threshold (Haug, 1993). Concentrations that elicit annoyance, intolerance and irritation can be several times greater than the recognition threshold. For odors in general, Das (2000) states that odor complaints tend to occur at concentrations that are 5 times the detection threshold. Therefore, an odor concentration of 5 D/T at the location of a sensitive receptor seems to be a reasonable target for minimizing odor impacts off site. Achieving the 5 D/T concentration, or any other target, does not guarantee the elimination of odor complaints. It is simply a target for managing.

Intensity

Like concentration, odor intensity relates to the strength of the odor. While the intensity is strongly affected by the concentration, the nature and quality of the odor is also a factor. Thus, strength is a better indication of the acceptability of an odor than concentration (Dravnieks and O'Neil, 1979 after Haug, 1993). Intensity reflects an odor's *staying power* or pervasiveness.

Some evidence suggests that odor complaints begin at odor intensities above 3.5 on the butanol intensity scale. Ratings from 4 to 6 correspond with a possible to probable nuisance and 6 to 8 would definitely be a nuisance (Haug, 1993).

Duration

In general, people become less tolerant of an annoying odor the longer that the odor lingers. The duration required to push a person over the tolerance line depends on the intensity and character of the odor. The odor science and composting literature reviewed provide no numerical guidance about duration and odors. For example, the literature suggests no data to indicate how long the average person will endure an odor of given strength and hedonic tonic tone before she/he takes action or lodges a complaint.

There is an effect in which a long duration of odor can increase tolerance. When exposed to a constant odor level, people tend to adapt to it. Their sensitivities and perceptions of the odor decrease (Dalton, 2003a). This adaptation is one explanation for why the last people to recognize an odor are often the operators at landfills, farm composting sites and wastewater treatment facilities.

Frequency

Frequency has a similar influence as duration on odor tolerance. People are less tolerant when odors that come-and-go frequently come. Again, there is no data in the literature to suggest what frequency levels are critical to triggering an odor complaint or how the interval between incidents affects the situation. Intuitively, one would suspect that shorter intervals stress a person's tolerance. However, the intervals may be less important than the number of incidents that have occurred.

Repeated odors also appear to have a cognitive effect. In fact, the effect of repeated odors is the opposite of the adaptation that occurs with the extended duration of a continual odor. When an odor disappears and then returns, an individual recognizes the returning odor more readily than the initial odor of the same strength. A learned recognition occurs. This effect is much more prominent in females than males, possibly due to evolutionary influences concerning the need to identify offspring (Dalton, 2003a).

Timing

People are upset by odors when the odors interfere with their lives. Odor episodes that intrude at critical times bring quicker and stronger reactions. Examples of bad timing for bad odors include holidays and weekends during nice weather, mornings while children are waiting for school buses, during school recess periods, dinner hours and generally any time that people are enjoying activities outdoors. Awareness in scheduling composting activities can go a long way toward avoiding problems during some key periods, like weekends. Unfortunately, several of these critical times coincide with the worst atmospheric conditions, such as temperature inversions and slight winds (e.g. mornings and early evenings).

Reaction—Attributes of Odor Sensing Individual

Individuals differ greatly in their perceptions of odors. However, the differences in people's reactions to odors go well beyond their olfactory perceptions. People also interpret and respond to odors according to their historic associations, attitudes and expectations. In an excellent article in BioCycle magazine (Dalton, 2003b), Pamela Dalton, psychologist with the Monell Chemical Senses Center, writes the following. "Research has shown that people's reaction to odor and their beliefs about the effects from odor are influenced by a diverse set of factors including personality traits, personal experience and information or social cues from the community and media. These factors can increase, or in some cases decrease, a person's sensitivity and awareness of environmental odors." In short, what an individual feels and believes about an odor influences his/her response.

Dalton's research, described in the BioCycle article, demonstrates the influence of two psychological factors on odor perception—expectations and social cues. In one experiment, three different groups of volunteers were exposed to 20 ppm of n-butyl alcohol, which is not pleasant smelling but not an irritant at that concentration. Beforehand, one group was given a positive bias by telling them that the chemical was a natural plant extract. The second group was told that the chemical was a standard laboratory odorant (neutral bias). The third group was told that it was an industrial degreasing chemical (negative bias). All three groups were exposed to the same concentration of the same chemical. Nevertheless, the group given the negative bias reported significantly greater symptoms of throat, eye and nose irritation than the neutral bias group. The positive bias group reported significantly fewer symptoms.

In another experiment in Dalton's lab, three groups of volunteers were asked to smell an unidentified odorant (acetone was used). Planted within each group was a "confederated subject"—a paid actor who was instructed to orally respond either positively (e.g. increases alertness), negatively (e.g. irritates eyes) or in a neutral manner. The volunteers were asked to rate the odor intensity every minute over the 20-minute exposure duration. The odor intensity ratings for the groups hearing the positive and neutral biases generally decreased during the experiment. The decrease was due to adaptation, which typically occurs during continued exposure to a constant odor. However, the odor intensity ratings of the negatively biased group increased over time. The negative comments of the confederate subject influenced the other volunteers that the odor was getting more intense. In addition, the negatively biased group reported significantly more nausea, drowsiness and eye and nose irritations.

Negative expectations are likely to prompt a negative response. When neighbors are already conditions to expect malodors from a composting facility they are more likely to notice them. Furthermore, they will perceive more serious consequences when they believe the odors present risks. They may even feel ill in the absence of harmful chemicals. Whether they know it or not, an activist neighbor protesting a facility is conditioning other neighbors to perceive the situation in a negative manner.

Odor Assessment

Executive Summary

Odors from composting facilities are widely understood to be the number one reason composting facilities experience problems, leading to relocation or closure in extreme cases. In an effort to better understand what specific factor leads to odor problems, the C-CORP project team and CIWMB staff created a list of ten facilities which were known to have had odor problems. In some cases the odor problems had been resolved, in other cases the odor problems had contributed to the closure of the sites.

Each site was evaluated against a series of “Factors contributing to odor issues at composting facilities.” Of the nine major factors identified, encroachment by urban development was the number one factor listed as a contributor among the ten sites, though most sites had a combination of factors which contributed to its particular situation. These factors can now be used as part of the evaluation of an existing site or in the planning of a new site to better understand the challenges a given facility might face.

Odor Assessment

Factors Contributing to Odor Issues at Composting Facilities

The following factors have been identified as contributing to odor issues at composting facilities. The C-CORP project team and CIWMB staff identified ten composting sites (6 operating and 4 closed) that had had odor problems. Although it is rarely only one factor that contributes to the closure of a site, odor was a major cause of the closure of the 4 sites studied. The following factors contributed to the odor problems suffered by these facilities. THE SITES HAVE NOT BEEN IDENTIFIED TO PROTECT THE INNOCENT. The factors are listed in prioritized order, but most sites had more than one of these factors contribute to their odor issues.

Encroachment

Even the most well sited facility can fall prey to encroachment, having less-compatible uses surround and advance upon it. Siting the facility in an appropriate site, near to similar uses with similar impacts can help reduce the potential for encroachment, but only active zoning enforcement (assuming the facility is sited in the appropriate zone) can truly prevent encroachment. Encroachment appears to be the number one contributor among the ten sites studied.

Original Siting Issues/Land Use

Although there are a number of sources for guidance on the appropriate method of siting a composting facility and the aspects of an appropriate site, not all developers avail themselves to this guidance. Some sites will be inherently more difficult to manage without odor problems.

Feedstock

Although all feedstocks emit odorous compounds, some are more likely to create odors during rapid decomposition. Some feedstocks like grass, or green material containing significant amounts of grass, may arrive at the facility in a malodorous condition. These highly putrescible (quick to biodegrade) feedstocks, such as food waste, biosolids, etc. may need to be handled differently than less readily degradable materials such as wood and green material. Other materials, even less highly biodegradable feedstocks, may create odors if left to sit for long periods of time prior to being blended and composted.

Competing Odor Sources

Competing odor sources are probably underrated as a contributing factor to odor problems. In some cases a facility was sited intentionally near other odor sources in an attempt to be with like uses. However, competing odor sources can have negative effects on a facility, especially if the facility has other issues as well. If a compost facility is sited near a competing odor source it may aggravate issues the neighbors may already have with that odor source and they may turn their displeasure on the composting facility. In addition, odors from two or more facilities may commingle and change, especially over distance.

New Feedstocks Processed

Accepting new and unfamiliar feedstocks should be approached with caution until their behavior is understood in the subject facility. While accepting new and unfamiliar feedstocks may be a contributing factor to an odor issue at a composting facility, it does not appear to have been a major factor in the ten sites examined. It may have been a minor contributing factor in two of the ten sites.

Changes in Processing Methods

Major changes in processing or composting methods can be a contributing factor to odors. Changes in process may take several months to be proven effective, or the opposite. However, this does not appear to have been a major factor in the ten sites studied. Changes in processing methods may have been a contributing factor in two of the ten sites studied.

Equipment Failure

Most composting facilities rely on major processing equipment for grinding, material handling, turning windrows and screening. Failure of a key process component can lead to process problems (i.e., if the grinder breaks down and is not easily replaced, feedstocks can sit for long periods of time prior to being processed). While equipment failure can lead to short term problems, these are perhaps the most readily remedied. Operators can rent or lease processing equipment while repairs are made. In some cases, operating permits require the provision of back-up equipment. Equipment failure may have been a contributing factor in two of the ten sites evaluated.

Increase in Volumes Processed

An increase above and beyond the “normal” volume of feedstock processed can be a significant cause of odors, particularly if the site is not designed to operate at the increased capacity. Significant increases in feedstock on a regular basis (beyond the occasional “peak” loading rate) can contribute to odors. If a site is not designed for handling the extra material the entire process can suffer; material is not ground expeditiously, windrow heights are exceeded, material is composted for less than the required time in order to expedite shipment off-site, etc. All of these problems can create or contribute to odor problems.

Weather Impacts/Unique Weather Patterns

Weather impacts are a complicated subject and relate to the initial siting of a facility as well as day-to-day operations. Weather impacts are discussed in much greater detail in the *Literature Review* section. The most common weather impact in California is an inversion layer. Temperature inversions act like a lid, trapping odorous air in the general vicinity and reducing the impact of “normal” odor dispersing winds**.** Topography also plays a role in transport of odors from a compost site.

The findings are summarized in Table 7. Other factors that can contribute to an odor issue are discussed in the *Literature Review*.

Table 7: Factors contributing to odor issues at composting facilities: top 10 list

Site	Feedstock	Original Siting Issues/Land Use	Encroachment	Competing odor sources	New feedstocks processed	New/changes in processing methods	Equipment failure	Increase in volumes processed	Weather impacts/Unique weather patterns
A	Biosolids	No	Yes	No	No	No	No	No	Minor factor
B	Green material/food material	No	Yes	Yes	No	No	No	Minor factor?	Yes
C	Wood waste/green material	No	Yes	Yes	No	No	Minor factor?	Yes	Yes
D	Biosolids	Yes	No	No	No	Maybe	No	Possible factor	No
E	Mushroom substrate	Yes	No	No	No	Maybe	Minor factor	No	No
F	Green material	No	Yes	Sometimes	No	No	No	No	No
G	Green material, food waste	No			No		No	No	Minor factor
H	Green material, manure	Yes	No	No	No	No	No	No	No
I	Green material, grape pomace		No	No	No	No	No	No	No
J	Green material (biweekly)	Yes	No	No	No	No	No	No	Minor factor

Mitigation Alternatives Research

Executive Summary

Among the mitigation alternatives investigated in this study, the use of finished compost as a blanket and part of the blend yielded the most conclusive and significant results. For terpenes, ammonia and reduced sulfur compounds, both of these alternatives yielded a substantial emission reduction.

However, neither the blanket nor the inoculum results were conclusive for mercaptans largely since they were not found in most samples. Both mitigation alternatives seemed to be ineffective in reducing the organic acid emissions; however, it is important to note that it was observed that both the feedstock and the finished compost emitted similar levels of organic acids. Therefore, the use of compost blanket and blend should not be viewed as ineffective but rather that the feedstock has not resulted in organic acid emissions more than the finished compost.

It is also important to note that the use of a compost blanket and compost blend deserves a special attention. This is because the finished compost as a part of the blend describes the situation after a turning event when finished compost was used as blanket. The results clearly suggest a continued reduction effect even after the finished compost blanket gets incorporated with the pile after a turning event.

Misting was found to be ineffective for control of terpene and organic acid emissions. It had a negative impact for ammonia emissions at low application rates, yet considerably lowered the emissions at high application rates (beyond 2.5 L/m^2).

Odor neutralizing agents yielded results that were either non-effective or inconclusive, except for ONA#1 for control of reduced sulfur compounds. In this case, this particular ONA seemed to be effective in controlling emissions beyond two days.

Oxygen releasing compounds were effective in reducing the emissions of sulfur compounds while it was ineffective for organic acids. Further, these oxygen compounds had a negative impact on ammonia emissions. Hydrogen peroxide was tested for sulfur compounds and organic acids and data was inconclusive.

Several of the targeted compounds were not generated by the tested feedstock. There were several observations made that we believe might have caused this. In most cases, the material was saturated with water due to intense precipitation throughout this study. It is commonly accepted that saturated compost material would cause generation of malodorous compounds.

However, at the time of collection, material was almost free of odor. Even in the vicinity of the facility, the material was free of odors compared to the sunny days. Our further investigation revealed that material was basic (pH>8.5) which would cause many of the targeted chemicals such as hydrogen sulfide, mercaptans and organic acids to ionize and render them less volatile. The cause of the high pH conditions could be attributed to paper pulp and/or lime stabilized biosolids.

Furthermore, the material had very poor structure—it had a muddy-like appearance in most cases. This could have also sealed the surface and blocked the flux of chemicals which could have caused entrapment of the compounds within the pores of the material and decompose. In addition, as described in the *Literature Review* section, most of the

emissions in a windrow or passively aerated composting system results from the flux of air created by the temperature profile. As the temperature in the inner parts of the compost matrix heats up, the warmed air rises up with the (odorous) compounds and causes the emissions from the surface. The size of the experimental containers might have been insufficient in this project to generate enough heat to cause the flux of air.

Readers are cautioned not to rule out any odor mitigation alternative based on the results of this study. In many cases the targeted odorous compounds were not generated and therefore, the efficacy of the mitigation alternative could not be measured. We did conclude that the blend of materials—biosolids-paper pulp-bedding, used in this study might not suitable for all target compounds. However, due to the time limitations and logistical issues of obtaining desired materials on a consistent base, the change of the experimental design was not possible.

Introduction

Communities throughout the world have been increasingly challenged to manage disposal of their waste as a result of environmental consciousness and rapidly shrinking landfill volume. Siting new landfills is at best a hardship, and getting closer to the being "impossible" due to public opposition and ever complicated political process.

Thus, the government agencies are compelled to divert as much waste as possible from landfills. Public agencies in numerous jurisdictions have adopted regulations limiting disposal of otherwise useful waste materials. In 1989, the City Council of Vancouver, BC, passed a resolution to reduce the municipal solid waste (MSW) by 50 percent (Henderson 1999).

The Onondaga County, NY, Resource Recovery Agency banned disposal of grass, leaves, and prunings into the landfills in 1992 (LaLonde 2000). Since the early 1990s, approximately half of the states in the U.S. have banned yard waste from landfill disposal. The California legislature took the concept further with the passage of the Integrated Waste Management Act, which required all counties to divert 50 percent of MSW from landfills by the year 2000 (CIWMB 2005).

Characterizations of the MSW reveal that about half of the waste stream is composed of biodegradable organics (U.S.EPA). It has been estimated that more than 40 percent of the municipal solid waste (MSW) generated in the state of California is biodegradable Thus, a large portion of the MSW stream can be diverted from landfills by recycling the biodegradable organic waste components like yard trimmings and food residuals.

Composting offers a cost-effective means of treating the biodegradable portion of the MSW. Indeed, composting can turn "waste" material into a valuable product, compost. However, composting doesn't come without consequences. The composting produces variety of volatile compounds, some of which are considered malodorous.

When such compounds persist in high enough concentrations, and then travel to neighboring residences and businesses, odor complaints are likely to arise. In many cases, intense urban encroachment has severely reduced, if not eliminated, the odor-dispersing buffer space between composting facilities and their neighbors. . Many facilities that were once isolated are now within the sight and smell residential and commercial establishments. The increasing numbers of odor complaints have made composting facilities the center of attention for the public and the local enforcement agencies.

Odor emissions from composting facilities, and their off-site impacts, can threaten the continued operation of the facility. Urban encroachment has contributed to the problem and has put more facilities in peril. There is now an acute need to find mutually acceptable solutions to odor emissions from composting.

Failing to find such solutions threatens the viability of the composting industry and the environmental benefits that the industry brings – both in regard to waste management and the benefits of the compost. There has been good deal of interest focused on the manipulation of the composting process to control the formation of odorous compound. However, mitigation alternatives to prevent and/or control their emissions haven't received much attention.

In 2004, the California Integrated Waste Management Board (CIWMB) initiated a project in partnership with San Diego State University to develop solutions to odor complaints plaguing an increasing number of facilities. The project, known as the Comprehensive Compost Odor Response Project, or CCORP, is a multi-facetted project that seeks to provide odor-management tools to local enforcement agencies (LEAs) and to composting facilities operators.

The hope is that these tools will help prevent and positively resolve conflicts between facilities and the neighboring communities without closing or impairing the composting operation. CCORP included a research component that developed mitigation strategies to control the generation and/or emissions of common odorous compounds during composting. The report presents the results of that research.

Project Scope

The common odorous compounds emitted from composting facilities include terpenes, reduced sulfur compounds, ammonia and other nitrogenous compounds, and volatile fatty acids (Rosenfeld, 2005). These compounds are released either directly from the feedstock or as a result of biological breakdown of the feedstock. This study employed bench-scale composting reactors to investigate the ability of selected mitigation measures to control the emissions of common odorous compounds.

In September 2004, a project initiation meeting was held at the CIWMB to select the feedstock and mitigation alternatives that are the most relevant, practical and economical to be investigated in this study as well as the experimental approach. The participants were the Board staff, project members and other experts. The following decisions were made:

The chemical classes to be targeted:

- Terpenes
- Nitrogenous compounds
- Ammonia
- Amines
- Cadaverene
- Putrescence
- Sulfurous compounds

- Mercaptans
- Reduces sulfur compounds
- Volatile organics acids
- Other organic compounds

Feedstock chosen to be studied:

- To study terpene emissions ground prunings were selected. The Miramar Green Waste Composting Facility (MGWCF) was identified as the source.
- To study the remainder of the chemicals listed above, a 1:3 v/v blend of biosolids (from the Metropolitan Biosolids Processing Center, San Diego) and woodchips (from MGWCF) was originally selected. It should be noted that when ammonia and other nitrogenous chemicals were studied, no such emissions were identified from the blend of biosolids and woodchips. Therefore, chicken litter obtained from the Hilliker Egg Range was used in lieu of biosolids. To study remainder of the chemicals, the feedstock was switched back to biosolids blended with woodchips. However, the disposal of the materials became an issue and it was therefore decided a composted material made from a blend of biosolids, paper pulp and straw bedding from Synagro Composting Facility located in Corona, CA.

The mitigation alternatives to be studies:

- Finished compost as a blanket layer
- Finished compost as an inoculum
- Misting
- Commercially available odor neutralizing agents (ONAs)
- Oxygen release compound (ORC) (excluding terpenes study)
- Topical hydrogen peroxide (H2O2) application (only for reduced sulfur compounds)

General Research Approach

At the project startup meeting, there was a discussion on how to best simulate the natural conditions in laboratory-scale as best as it can be achieved. It was decided to place the proper material blends in passively aerated plastic bins to allow development of the conditions and generation of the targeted compounds. The experimental setup consisted of 6 twenty-gallon containers (18-inch in diameter) having 8 aeration inlets with 2-inch diameter placed 4 inches above the bottom to facilitate passive aeration, and a sampling train having a trap specific to the type of compound being studied, a six channel rotameter and a vacuum pump as described in Figure 7.

The corresponding feedstock was placed into the containers, and the odor mitigation alternative was applied to the material as described below:

- Finished compost was laid over the container at a 0, 2, 4, 6, and 8 inches heights
- Finished compost was applied at the volumetric mixing rates of 12, 24, 35 and 45%, and blended with a concrete mixer

- Misting was applied topically at 0 (i.e. the control), 25, 50, 100, 250 and 500 ml
- ONAs were applied in different dilutions (0, 10, 25, 60, and 100%, diluted with water)
- ORC was blended with the feedstock at the rates of 0, 40, 80, 120 and 160g with the concrete mixer.
- Hydrogen peroxide was applied topically at the concentrations of 0, 2, 5, 7 and 10% in water.

In order to simulate the real world situation, the containers were left open, i.e., exposed to the air when there was no sampling. At the beginning of each sampling, first, sampling rate was adjusted to 200 ml/min, the lids of the container and adsorption tubes, then, were connected for 20 minute sampling. Samples were collected at 1st, 3rd, 6th hours and 1st, 2nd, 3rd and 7th days initially, then the 3rd and 7th day sampling was dropped since there were no effectiveness observed.

Initially 7 days of experiment duration was decided since the majority of the emissions occur with the first of the composting process. In the case of hydrogen peroxide, the batches were left outside being exposed to the sun during the day time to facilitate the free radical generation.

Using an odor panel was beyond the scope of this work due to its complexity and costs associated with it. Instead, specific odorous compounds listed above were targeted. The headspace air samples were taken using appropriate chemical trapping techniques and analyzed by analytical instruments including a gas chromatograph-mass spectrometer, gas chromatograph with a sulfur specific flame photometric detector and an ion chromatograph. The details of the sampling and analytical protocols are discussed in related sections.

Figure 7: Schematic of experimental setup

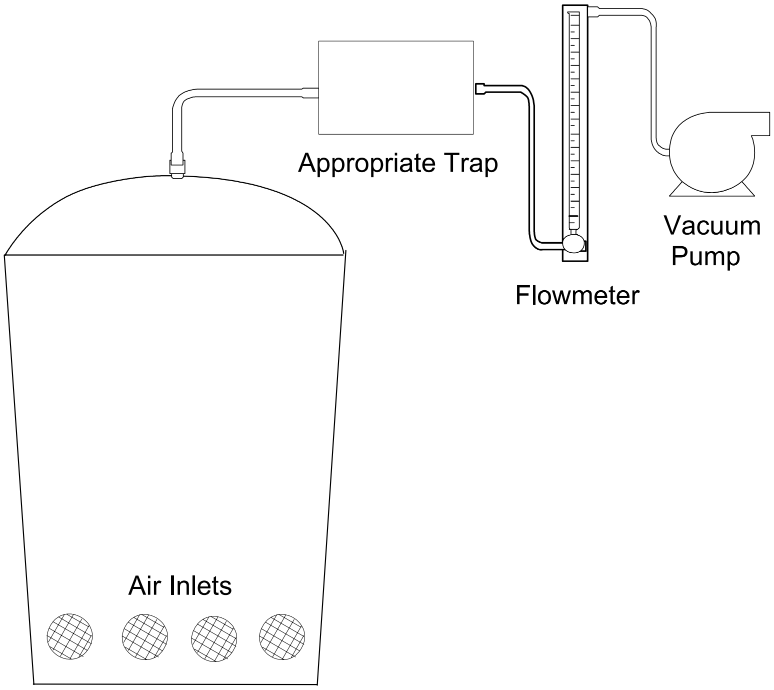
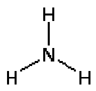
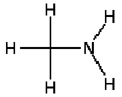
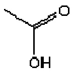
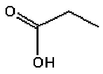
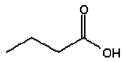
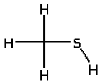
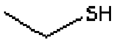
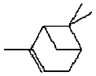
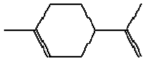


Table 8: Selected properties of the chemicals studied in this investigation

Chemical Name	Structure	Cas #	Solubility	pKa	Henry's Constant	Vapor Pressure (mmHg @25ºC)	Toxicity
Ammonia		7664-41-7	4.82E05 mg/l @24ºC	9.25	1.61E-05	7510	Inhalation human LCL$_O$=30000ppm/5min Oral Rat LD$_{50}$=350mg/kg
Methylamine		74-89-5	8.9E05 mg/l @30ºC	9.8	1.04E-04	1610	Inhalation Mouse LC$_{50}$=2400mg/m^3/2hr Oral Rat LD$_{50}$=90ml/kg
Dimethylamine		124-40-3	1.63E06 mg/l @40ºC	10.7	1.77E-05	1520	Inhalation Rat LC$_{50}$=4540ppm/5hr Oral Rat LD$_{50}$=698mg/kg
Trimethylamine		75-50-3	1.08E06 mg/l @25ºC	10.6	1.11E-05	2650	Inhalation Rat LCL$_O$=3500ppm/4hr
Putrescine		110-60-1	1E06 mg/l @25ºC	10.8	1.82E-09	4.12	Oral Rat LD$_{50}$=463mg/kg
Cadaverine		462-94-2					
Acetic Acid		64-19-7	1E06mg/l @25ºC	4.76	1E-07	15.7	Inhalation Mouse LC$_{50}$=5620ppm/1hr Oral Rat LD$_{50}$=3310ml/kg
Propionic Acid		79-09-4	1E06mg/l @25ºC	4.88	4.45E-07	3.53	Oral Rat LD$_{50}$=2600mg/kg

Chemical Name	Structure	Cas #	Solubility	pKa	Henry's Constant	Vapor Pressure (mmHg @25°C)	Toxicity
Butyric Acid		107-92-6	6E04mg/l @25°C	4.82	5.35E-07	1.65	Oral Rat LD_{50}=2gm/kg
Hydrogen sulfide		7783-06-4	437ml/100ml @0°C	7.04	8.56E-03	1.56E04	Inhalation Rat LD_{50}=444ppm
Dimethyl disulfide		624-92-0	3000 mg/l @25°C		1.21E-03	28.7	Inhalation Rat LCL_O =15850µg/m^3/2hr
Dimethyl sulfide		75-18-3	2.2E04 mg/l @25°C		1.61E-03	502	Inhalation Rat LC_{50}=40250ppm Oral Rat LD_{50}=3700mg/kg
Methyl mercaptan		74-93-1	1.54E04 mg/l @25°C	10.3	3.12E-03	1510	Inhalation Rat LC_{50}=675ppm
Ethyl mercaptan		75-08-1	1.56E04 mg/l @25°C	10.6	4.53E-03	529	Oral Rat LD_{50}=682mg/kg
α-pinene		80-56-8	2.49 mg/l @25°C		2.94E-01	4.75	Inhalation Rat LCL_O=625mg/kg Oral Rat LD_{50}=3700mg/kg
β-pinene		127-91-3	4.89mg/l @25°C		1.61E-01	2.93	Oral Rat LD_{50}=4700mg/kg

Chemical Name	Structure	Cas #	Solubility	pKa	Henry's Constant	Vapor Pressure (mmHg @25ºC)	Toxicity
Eucalyptol		470-82-6	3500mg/l @21ºC		1.1E-04	1.9	Oral Rat LD_{50}=2480mg/kg
d-Limonene		5989-27-5	13.8mg/l @25ºC		2.57E-02	1.98	Oral Rat LD_{50}=4400gm/kg

Control of Terpene Emissions

Materials

The freshly ground prunings were obtained on the day of each experiment from the Miramar Green Waste Composting Facility (MGWCF) operated by the City of San Diego. Upon arrival to the laboratory, it was screened for foreign objects, such as plastic and large pieces. There were 5 different commercial odor neutralizing agents (ONAs) studied in this investigation; due to the proprietary reasons, their names are not identified. The finished compost, which was utilized as blanket and compost blend, was also obtained from the MGWCF. The ONAs and the biofilter were applied as a topical and the compost blend was mixed with the prunings by a concrete mixer.

Analytical Method

The analytical method used in this study was based on a protocol that was described by Komilis and Ham (2000) and Komilis et al., (2004). Coconut shell charcoal organic trap adsorbent tubes (Orbo 32 ® 400/200, Supelco) were used to capture the terpenes from the headspace air. The contents of the adsorption tubes were emptied in to glass vials and combined with 4-ml of carbon disulfide and shaken for 30 minutes with a wrist-action shaker.

The vials were then centrifuged for 5 minutes. A 1-ml of the extract was transferred into an amber auto-sampling vial and spiked with 2 µl of 4,4'-dibromooctafluorobiphyenyl solution of 2µg/µl in methanol as the internal standard. Extracts were analyzed with a Hewlett Packard (HP) 6980 gas chromatograph and a HP 5973 mass spectrometer (GC-MS) equipped with a 30 m × 0.25 mm fused silica Valcobond VB-5 column.

The inlet and MS temperatures were maintained at 150°C an 300°C, respectively. Helium was used as the carrier gas at a flow rate of 1 ml/min, and a sample was injected with a split ratio of 1:50. The column temperature was initially maintained at 40°C for two minutes and ramped up to 250°C at a rate of 10°C/min. After holding at 250°C for 14 minutes, the temperature was raised to 290°C to condition the column for the subsequent run. The peak areas were normalized with respect to the internal standard peak area. The total terpene emissions are reported as the total normalized peak areas excluding the areas of internal standard and carbon disulfide, if present.

Results and Discussion

Adsorption and extraction efficiency of the adsorption traps were determined for a set of terpenes. The efficiencies were determined to be higher than 77% for all chemicals tested except for α –terpinene, which was determined to be 48.2%. The list of chemicals and the corresponding efficiencies are presented in Table 1. In order to determine the variability, samples were taken from all six containers having with equal mass of prunings without any treatment. The variability between the containers, measured as the percentage standard deviation with respect to the mean total peak areas, was determined to be 14% (Table 2).

Table 9: Trapping and extraction efficiencies for select terpenes

COMPOUND	EFFICIENCY, %	COMPOUND	EFFICIENCY, %
Camphene	89.2	Myrcene	91.4
3-Carene	79.1	α-Pinene	98.9
Eucalyptol	83.3	β-Pinene	88.1
Limonene	77.2	α –Terpinene	48.2

Table 10: Variation between the containers

ITEM	PEAK AREA	ITEM	PEAK AREA
Container #1	56105605	Container #5	41097711
Container #2	63706407	Container #6	50524058
Container #3	56236830	Average	53755849
Container #4	54864482	Std. Dev.	7517875

Effect of Compost Blanket

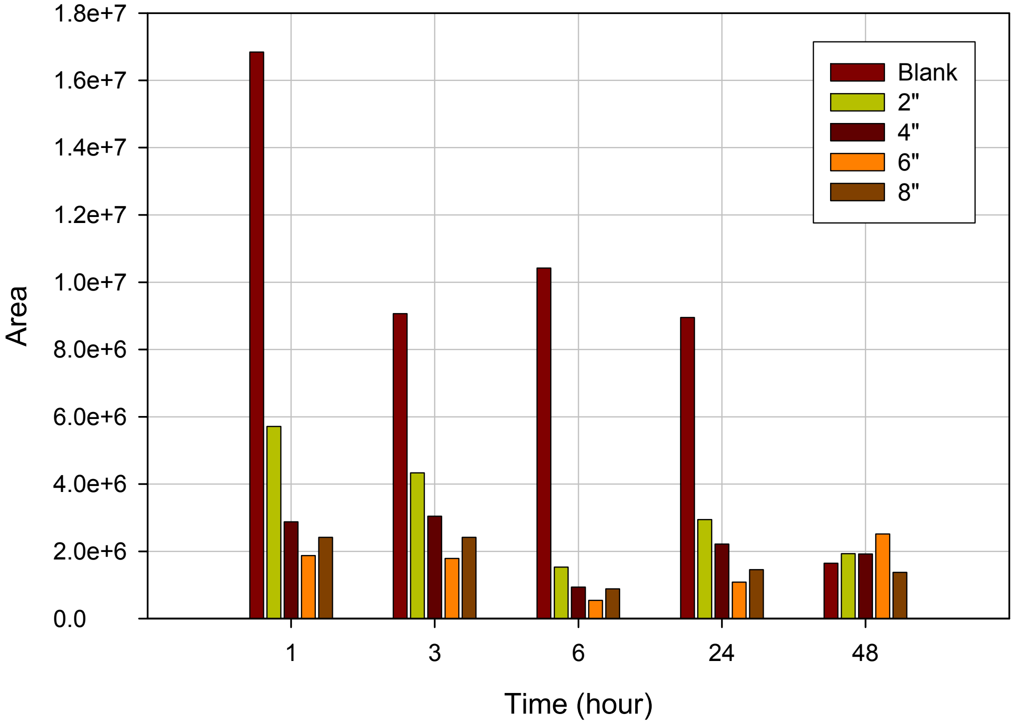
The finished greenwaste compost was applied on top of the fresh ground prunings as a blanket at different heights ranging from 2 to 8 inches. In the short-term (i.e., up to 24 hours), the application of finished compost resulted a substantial reduction, ranging from 51.5 to 98% on the total terpene emissions for all application rates (Figure 8). In fact, the results suggest that the bulk of the emissions might have derived from the compost blanket layer.

Emissions from the compost were substantially lower than those resulting from fresh feedstock. The flux of emissions from the feedstock was large blocked by the filter layer. The relative emissions seemed to be reduced as the emissions subsided for control while the treatments continued to emit at low level, and not because the efficiency of the biofilter layer was deteriorating. All treatment levels lowered the emissions. The finished compost layer was applied as a biofilter.

The efficacy of the biofilters using finished compost as media for the control of emissions has been well established in the literature (Abumaizar et al. 1998; Smet and Langenhove

1998; Leson and Winer 1991, and Chou and Büyüksönmez, 2006). The reductions in the emissions commonly attributed to adsorption and biodegradation of the compounds within the matrix. The results of this study suggest that finished compost layer can be a very effective and easy way of controlling the terpene emissions from composting piles. Since this alternative does not require acquisition of chemicals or costly emission control systems and only utilizes what is already available on site, it can be an easy and cost-effective way of controlling terpenes.

Figure 8: Total terpene emissions with compost blanket applications



Effect of Compost Blends

An active or finished compost often possesses a rich microbial diversity and activity, that can be missing at the early stages. Due to the lack of microbial activity, compounds may be slow to biodegrade initially. With this thought in mind, prunings were blended with finished compost as inoculum. This study yielded a very similar result as the compost blanket application in terms of the reduction of the emissions as presented in Figure 9.

The emissions were lower compared to the biofilter application; this can be attributed to the mixing of the prunings and the finished compost. It is likely that during the mixing, the VOCs in the pore space escaped to the atmosphere. The initial reduction rates ranged from 73.6 to 93.1% for 24% and 45% by volume applications, respectively. The reduction percentages decreased as the actual emissions subside over time. The addition of finished compost, due to its lower particle size, increased the bulk density of the combined material. The increases were determined to be 14.2, 16.5, 31.9 and 36.6% from the initial density of 0.65 kg/l for 12, 24, 35 and 45% application rates.

It should be noted that the finished compost is smaller in size, thus, it can cause reduction of bulk density when the blanket is incorporated with the pile at the next turning cycle of the composting pile. The increase in bulk density and reduction of the porosity can potentially hinder the aeration; never this can managed by increasing the mixing frequency, should it be an operational issue.

Effect of Misting and ONAs

Figure 10 presents the results of the experiment with misting. The results of the ONAs are given in Figures 11 through 14. Neither the misting nor any of the four ONAs did not result in any significant reduction in the emissions of terpenes over the course of the experiments.

It was surprising that none of these treatments resulted in lower emissions. We originally anticipated that these treatments would yield a lower emission due to the wet precipitation and solubilization effect considering the fact that most of these chemicals are fairly water soluble (see Table 10). It is possible that the volume of misting applied was not sufficient and/or their effectiveness lasted shorter than an hour. In this case, their effect would be missed since the first sampling was conducted an hour following the application of the mitigation alternative. Therefore, the application of misting and/or ONAs should not be ruled out based on the findings of this research.

Figure 9: Total terpene emissions with finished compost blends

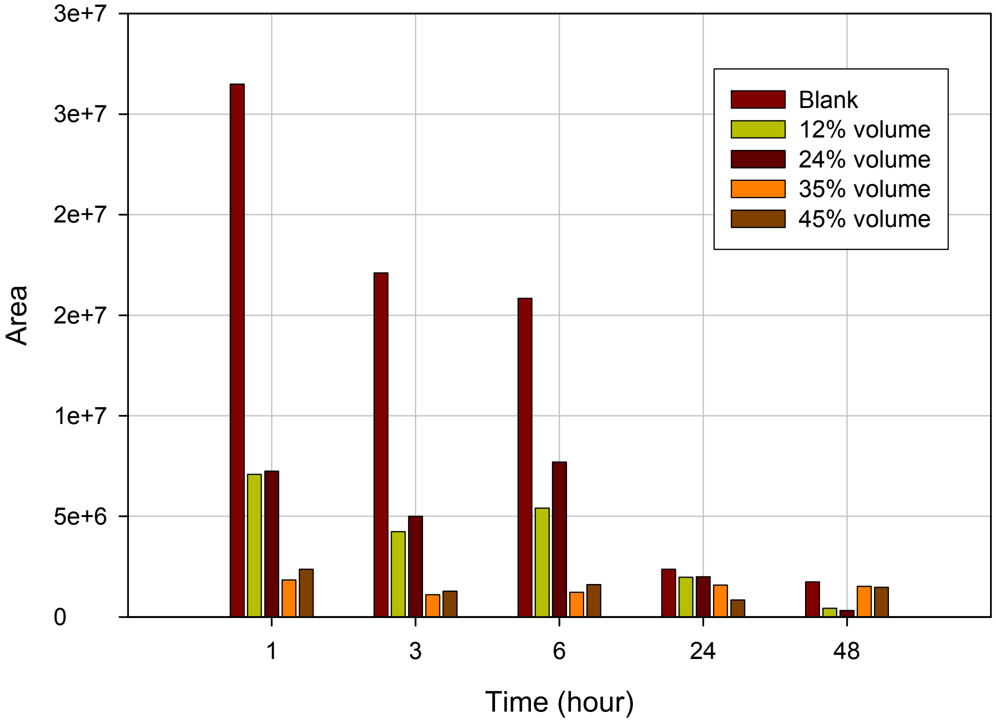


Figure 10: Total terpene emissions with misting

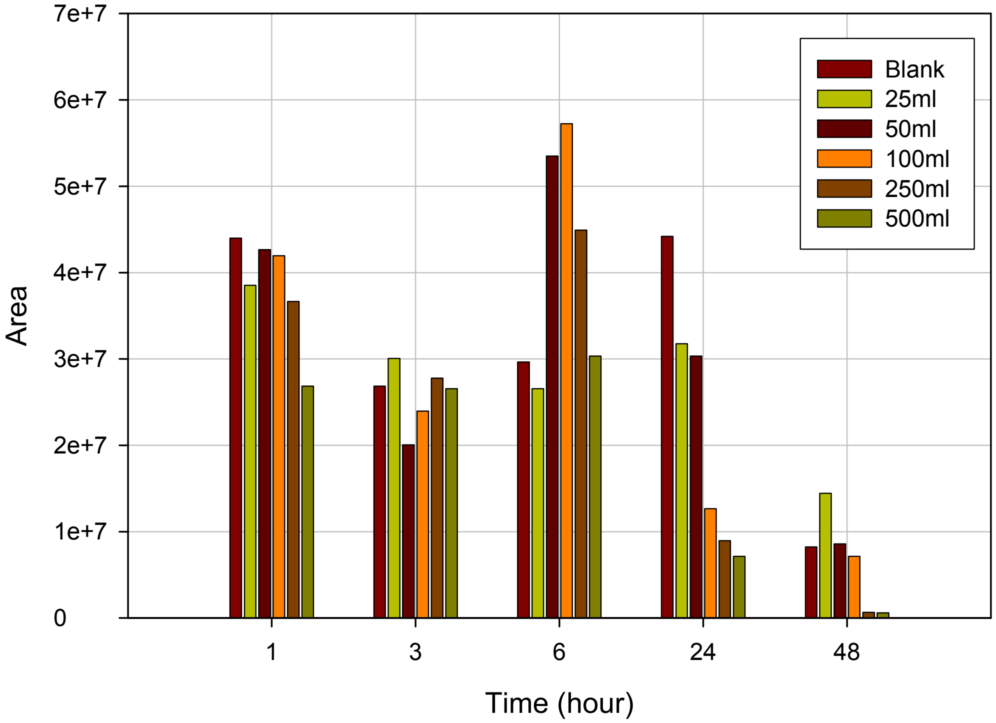


Figure 11: Total terpene emissions with ONA#1

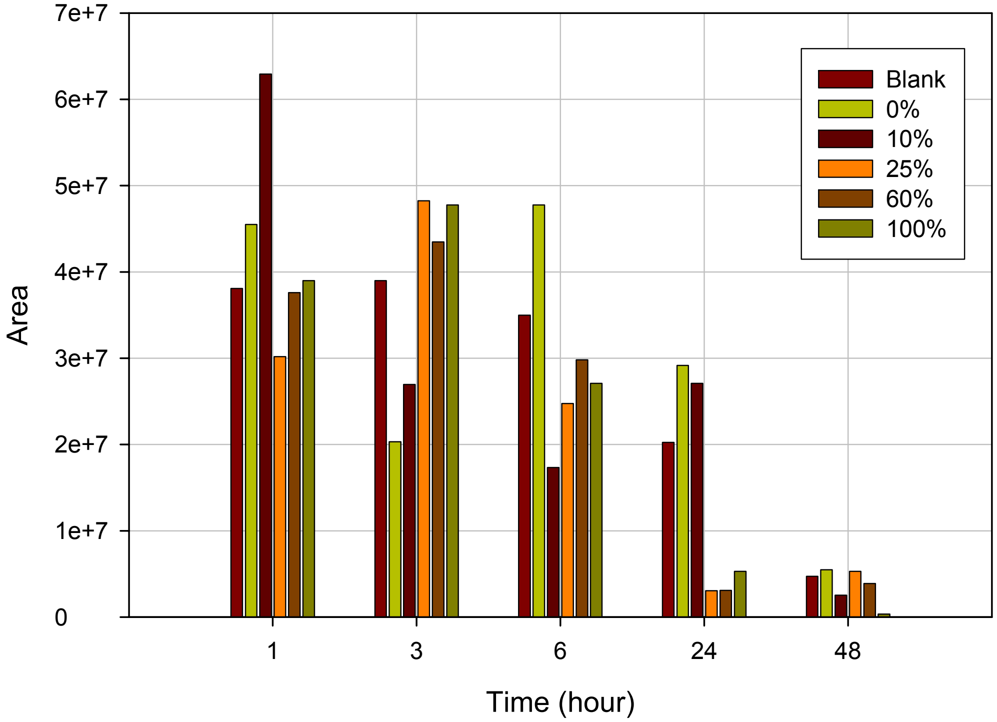


Figure 12: Total terpene emissions with ONA#2

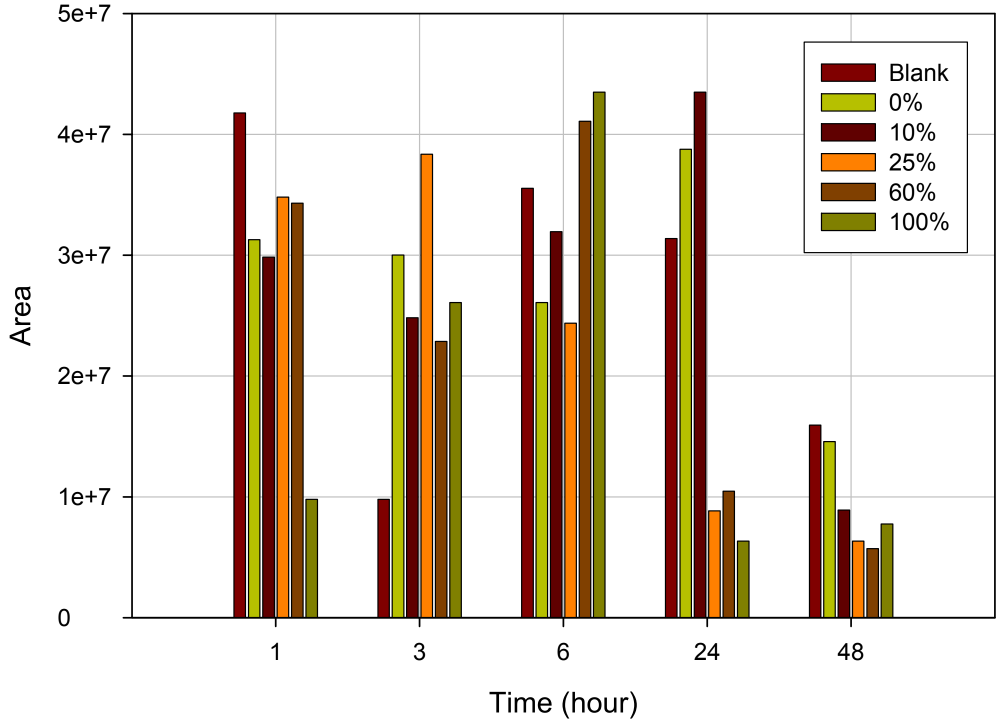


Figure 13: Total terpene emissions with ONA#3

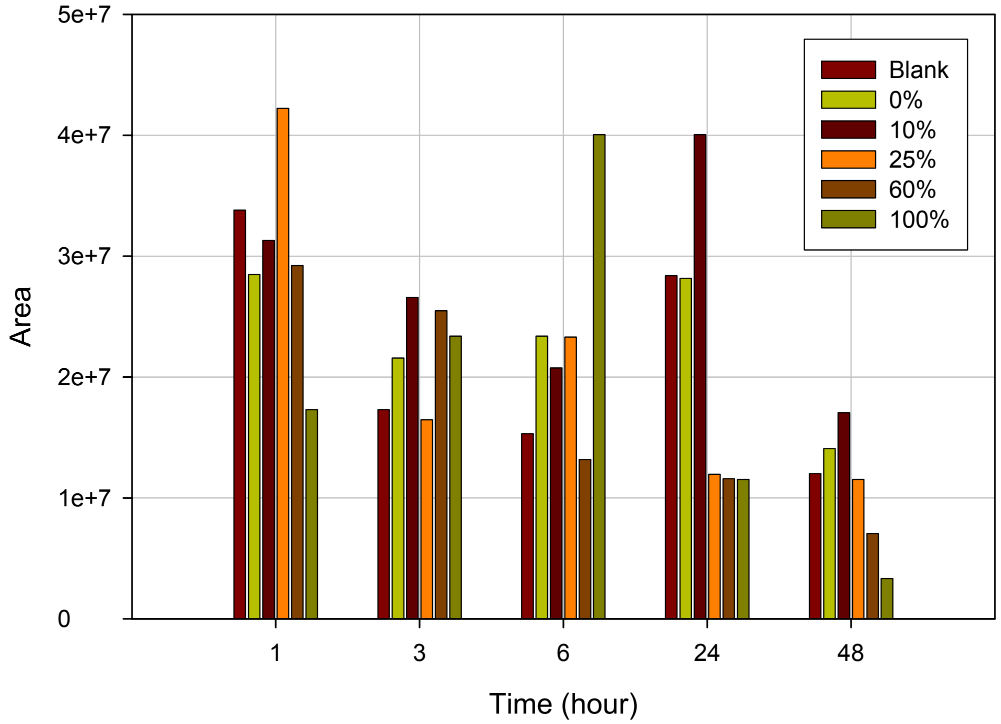
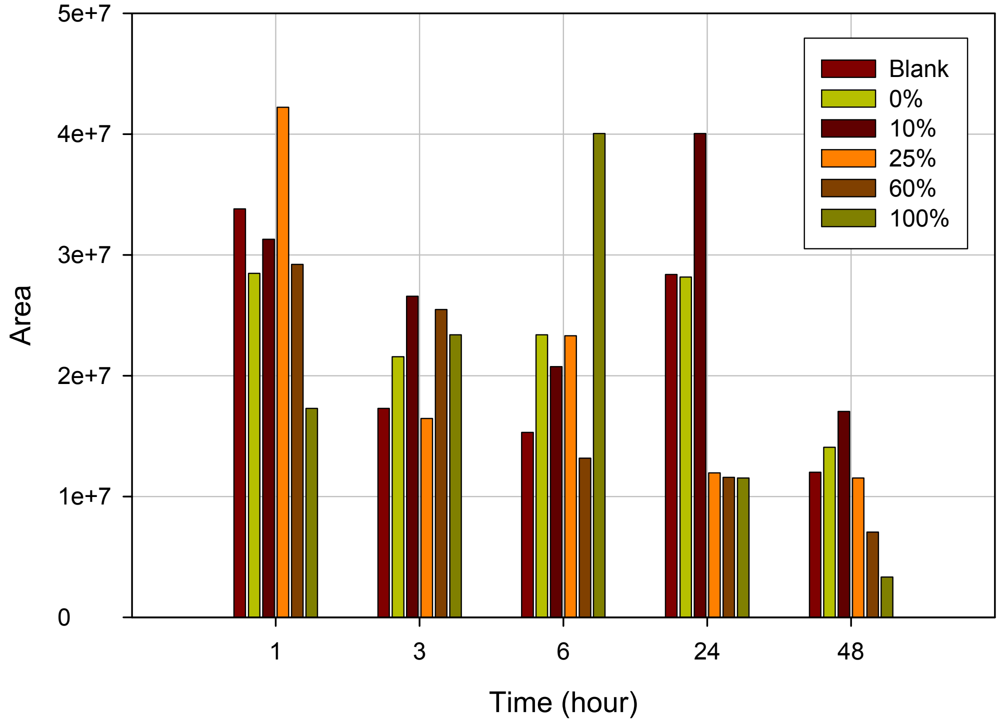


Figure 14: Total terpene emissions with ONA#4



Control of Nitrogenous Compound Emissions

Materials

The emissions of ammonia and amine were studied with a blend of chicken litter, bedding material compost and woodchips. Chicken litter and bedding material compost were obtained from the Hilliker's Egg Ranch and Hanson Composting located in Lakeside, California, respectively. Woodchips were obtained from the Miramar Green Waste Composting Facility (MGWCF). Materials were collected on the day of experiments and mixed with a compost-litter-woodchips ratio of 2:1:1 by volume with a commercial concrete mixer. The moisture content was increased to 29-34% by addition of water. The finished compost, which was used for the blanket and part of blend, was generated from the green waste and obtained from the MGWCF.

Analytical Method

Nitrogenous compound concentrations were determined by an ion chromatograph as discussed at Dionex Method (Document NO 031877-03). A Dionex DX-500 ion chromatograph (IC), equipped with a CG17A 4×50 guard and CS17A 4×250 Ion Pack separation columns was used in the conductivity mode with a CSRS Ultra II-4 mm electrolytic suppressor. The suppressor current was set to 100 mA. The samples were diluted ten times prior to injection to lower the acidity of the samples to obtain sharper analyte peaks.

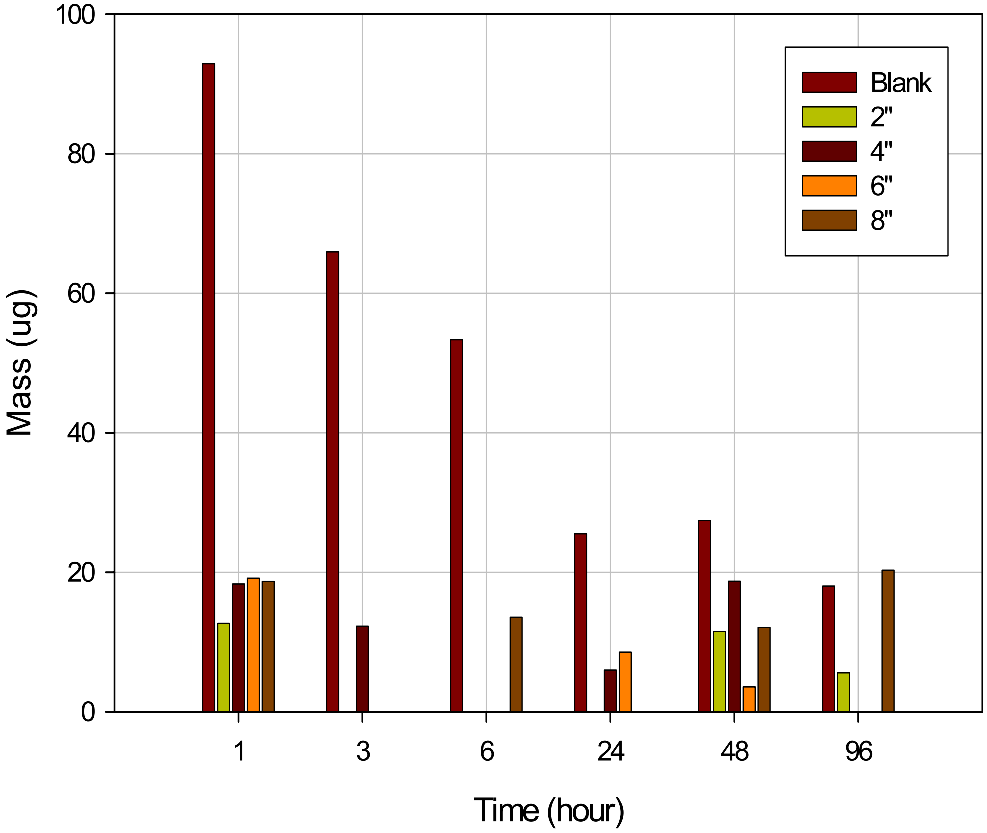
The sample injection volume was 200 μL. The eluent solution was methanesulfonic acid (MSA), which was run at 4 mM initially unteil 7th minute, than ramped to 12 mM for an additional six minutes and then reduced back to 4 mM to stabilize the system for 7 minutes prior to next sample injection. A blank sample, (i.e., deionized water) and a sample with known ammonia-nitrogen concentration were analyzed with each set of samples as a quality check.

Results and Discussion

Compost Blanket

The application of finished compost as blanket has resulted in a considerable reduction in the ammonia emissions. The achieved reduction was up to 86% for the first hour, and subsided as the experiment progressed as presented in Figure 15. However, it should not be interpreted as the efficiency of the blanket cover went down with time. The emissions from the bins with the blanket applications seem to be stayed fairly constant through out the course of the experiment; while, emissions from the control run subsided and reached to the level of treated runs with time.

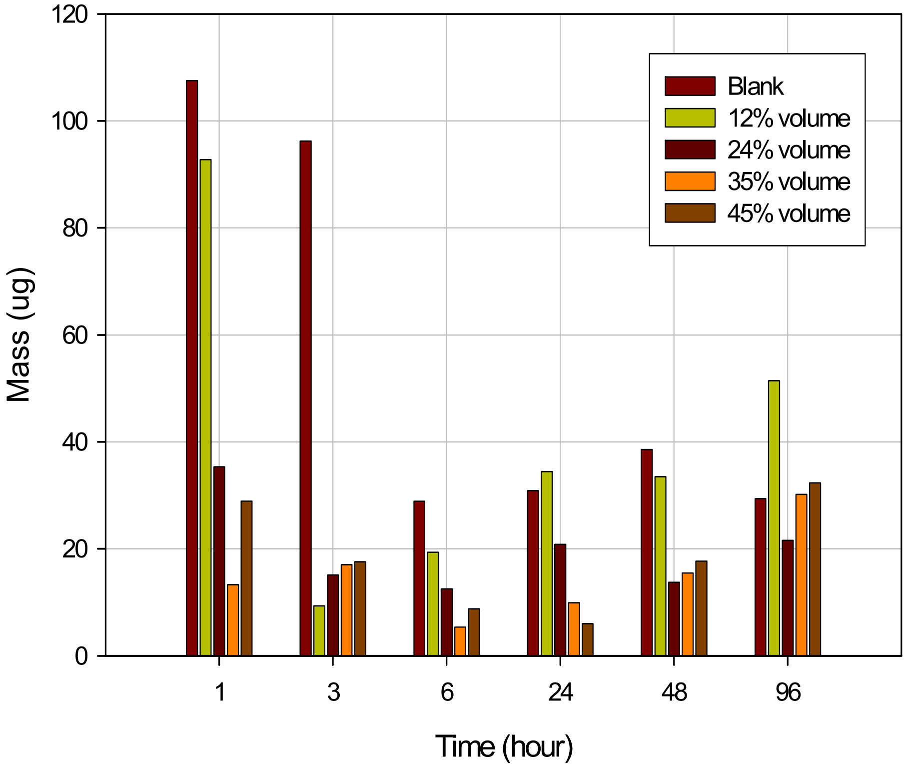
Figure 15: Ammonia emissions with compost blanket



Compost Blends

When the finished yard waste compost was blended with the chicken litter and woodchips, there were also considerable reductions at the ammonia emission levels (Figure 16). The use of finished compost as blanket and part of the blend had yielded comparable results. Furthermore, the addition of finished compost into the feedstock represents what happens at a composting facility after the first mixing event when it is applied as blanket, suggesting a continued effectiveness for reduction of emissions.

Figure 16: Ammonia emissions with finished compost blend



Misting

Misting with water resulted in an increase in ammonia emissions at lower application rates (i.e. 25, 50 and 100 ml); and significantly lowered the emissions at 250 and 500 ml applications (Figure 17). The increase at lower application rates is attributed to possible increase in biological activity on the surface. When a large volume of water was topically applied, there were considerable reductions in ammonia emission levels. This reduction can be explained by solubilization and dissociation of ammonia in water at high level of application.

ONAs

The ONAs yielded inconclusive results for ammonia emissions as presented in Figures 18 and 19. There was no pattern or correlation in anyway for both ONAs studied. The pHs of the ONAs applied were 3.65 and 2.04. Therefore, it was initially expected that the application of ONAs would result in lower ammonia emissions by ionizing the ammonia at low pH.

Nevertheless, apparently the acidity of the ONAs was not enough to lower the pH of the media since compost has a very high buffering capacity. Still, the results of this study suggest no correlation for use of ONAs for ammonia emission control. The application of ONAs in field-scale should not be excluded out based on the outcome of this study. It is important to note that this investigation was performed in the laboratory with substantially lower sample volumes. It is possible that the amount of material used or the test procedure was not representative of field conditions or applications.

ORC

The application of oxygen release compound (ORC) resulted in increased ammonia emissions in the short term; and seemed to have no effect beyond 24 hours (Figure 20). The increase in emission was also correlated with the application rate. ORC compound releases oxygen when hydrated, therefore, addition of ORC would increase the oxygen availability within the compost blend. This in turn probably caused an increase in the biological activity and released ammonia as the organic matter decomposed.

Figure 17: Ammonia emissions with misting

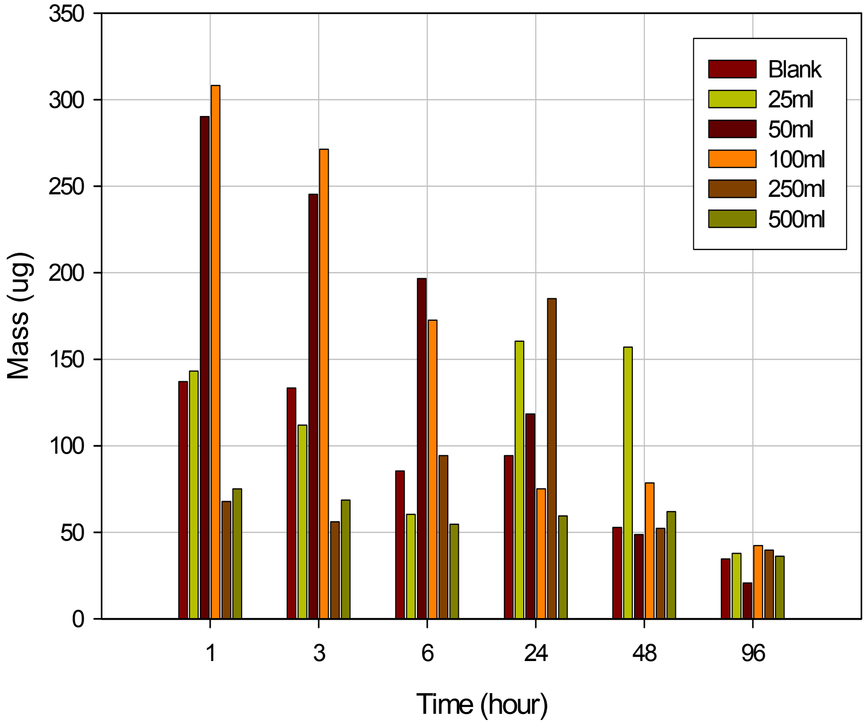


Figure 18: Ammonia emissions with ONA#1

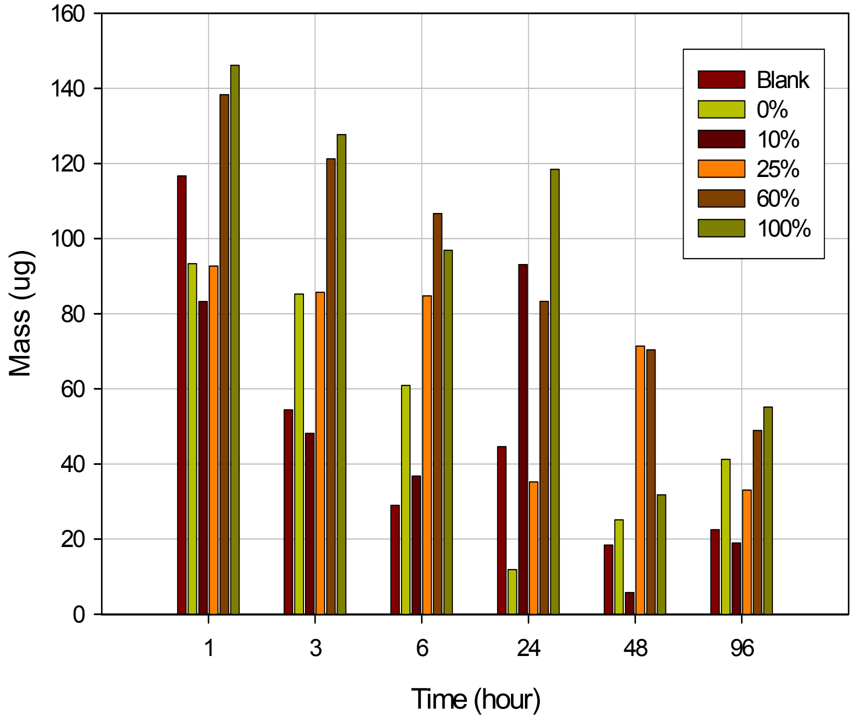


Figure 19: Ammonia emissions with ONA#2

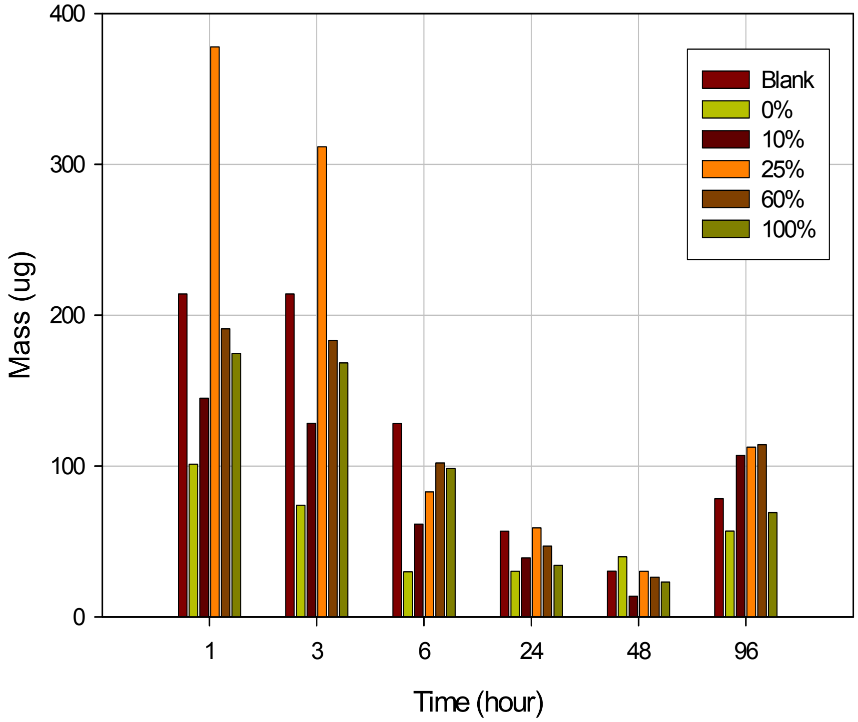
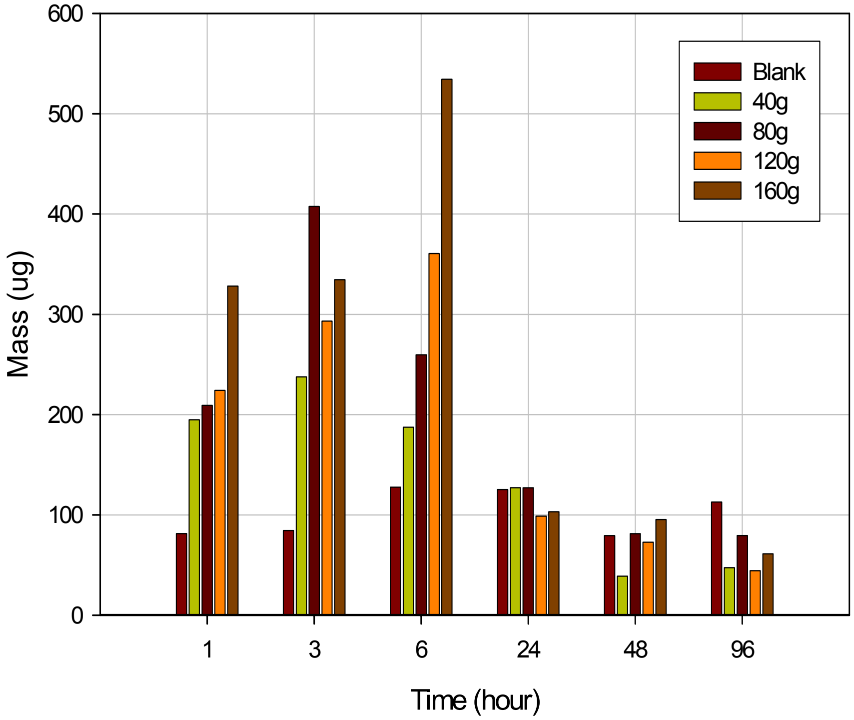


Figure 20: Ammonia emissions with ORC



The analytical method used was capable of detecting amines, putrescence and cadaverine as described by Dionex (REF). However, none of these compounds were detected in any of the samples. The chicken litter was dry and aged for an unknown amount of time when it was obtained. It is possible that these compounds that were derived from the breakdown of proteins might have already volatilized. Even though water was added at the time of blending chicken litter with woodchips, the duration of the experiments may not be long enough to generate detectable amounts.

Control of Mercaptan Emissions

Materials

The material was obtained from the Synagro Composting Facility located in Corona, California on the day of experiments. The material was a blend of dewatered biosolids, paper pulp and straw bedding material, and was collected from the inner section of a recently formed composting pile. Up on arrival at the laboratory, the mitigation alternative was applied and the target compounds—mercaptans in this case were investigated.

Analytical Method

Mercaptans were captured from the headspace and analyzed according to the Occupational Health and Safety Administration (OHSA) Method 2542. Samples were collected on glass-fiber filters impregnated with 5% mercuric acetate solution. The impregnated filters were placed in filter holder cassettes and wrapped with aluminum foil to prevent deteriorating due to exposure to light.

Following sampling, filter papers were removed from the cassettes and inserted into 40 ml amber vials containing a mixture of 20-ml of 25% (v/v) HCl and 5-ml of 1,2-

dichloroethane for extraction. Vials were extracted by a wrist-action shaker for 2 minutes and, then, centrifuged for 2 minutes to ensure phase separation and removal of fibers coming from the filter paper. One-milliliter aliquot from extract was transferred into amber autosampler vials and spiked with ethyl methyl sulfide, which was used as the internal standard for quality control.

The extracts were, then, analyzed by an Agilent 6890 GC equipped with a sulfur specific flame photometric detector (FPD). The column carrier flow (Helium) was maintained at 1 ml/minute; and the injection volume was 2 μl. The inlet and the detector were kept at 250°C. The column (DB-5, 30m, 0.250mm and 1.00 μm coating) was maintained at 30°C for 2 minutes and then ramped up to 200°C at a rate of 15°C/min. The sum of the areas, less the internal standard area, was reported as the total for mercaptans. The stated method efficiencies were 82.7, 89.3 and 93.0% for methyl, ethyl, and butyl mercaptans, respectively.

Results and Discussion

In most cases, mercaptans were not detected at all in any of the samples. We attributed this to the number of factors including the condition of the feedstock, amount of material, and possibly to the type of material used in this study. During the course of the study, we have experienced very heavy precipitation events. At the time of collection, the materials seemed to be saturated with water; there were no noticeable odor present in the material.

It should be noted that the human detection limit is 0.03 $\mu g/m^3$. Second, it is possible that the amount of material used in this investigation was not large enough to generate detectable amounts of mercaptans. Only two of the sampling events resulted in mercaptans; which were one of the ONAs and the ORC. Nevertheless, none of the results were sufficient enough to draw meaningful conclusions as presented in Figures 21 through 27. Further discussion is provided with the conclusion of this section.

Figure 21: Mercaptan emissions with compost blanket

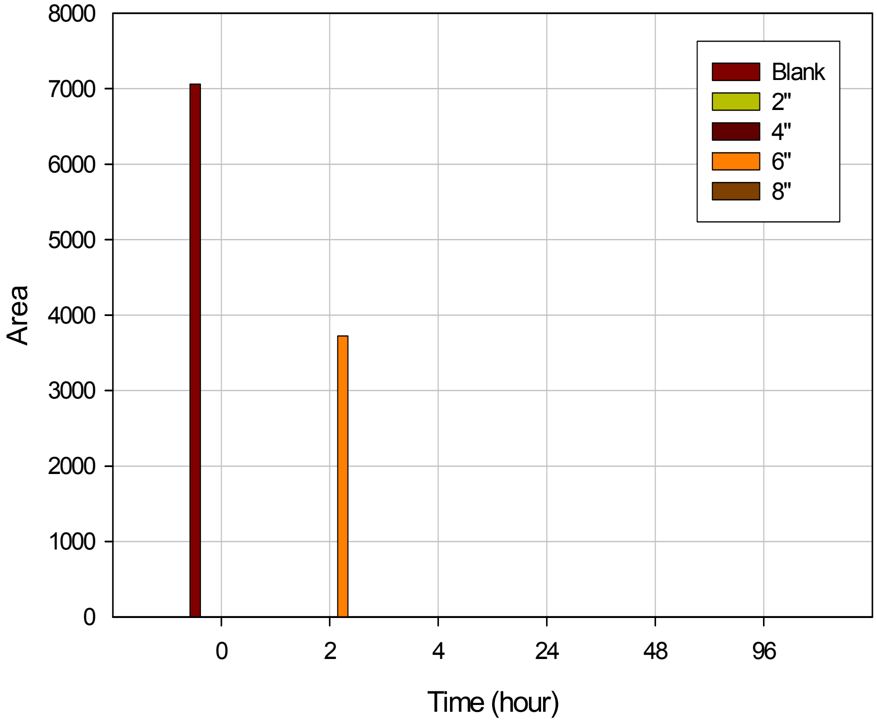


Figure 22: Mercaptan emissions with compost blend

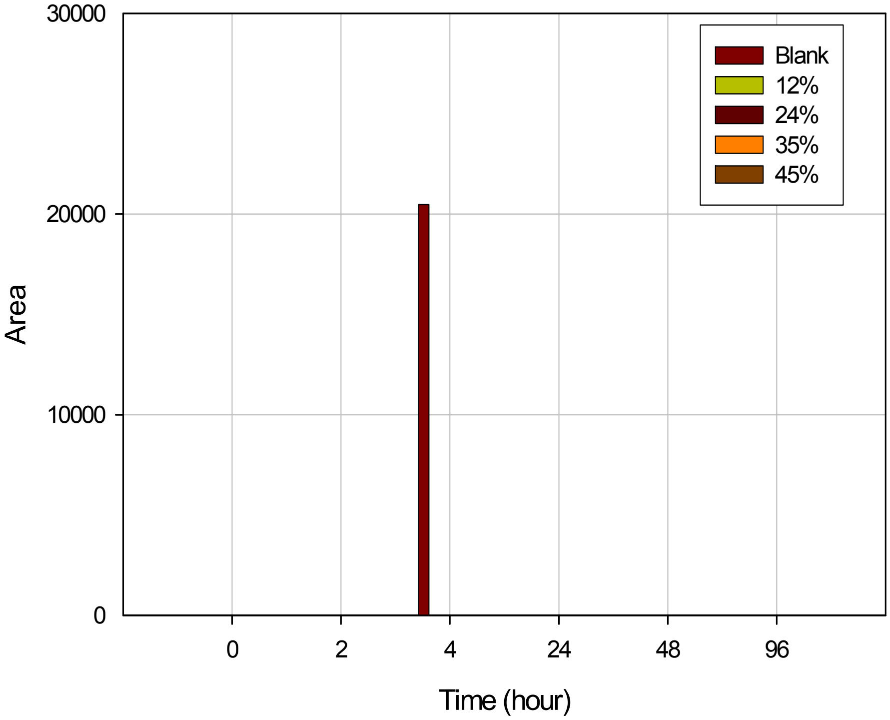


Figure 23: Mercaptan emissions with misting

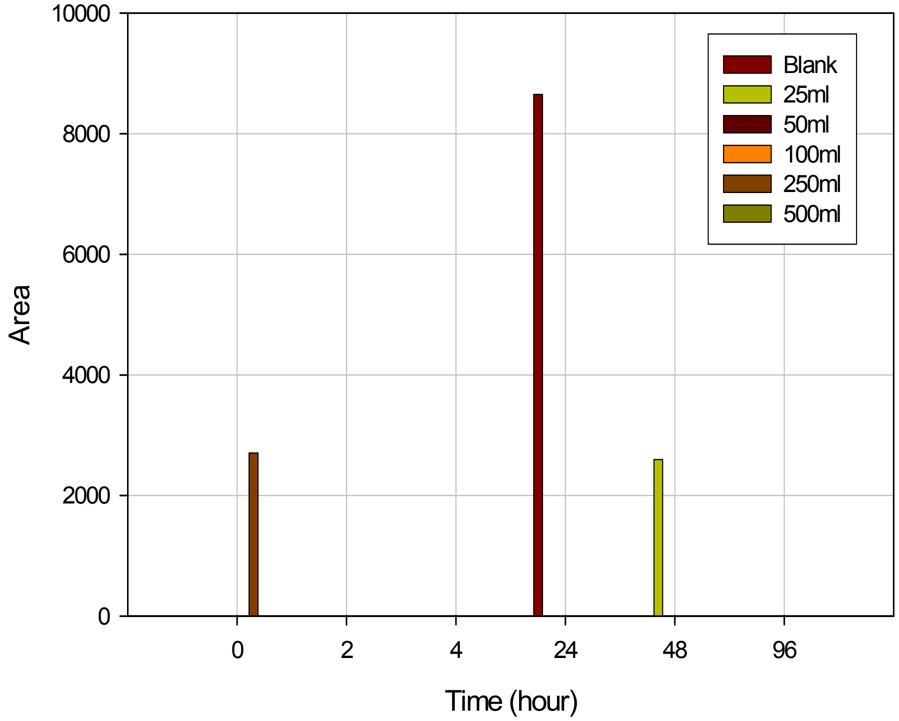


Figure 24: Mercaptan emissions with ONA#1

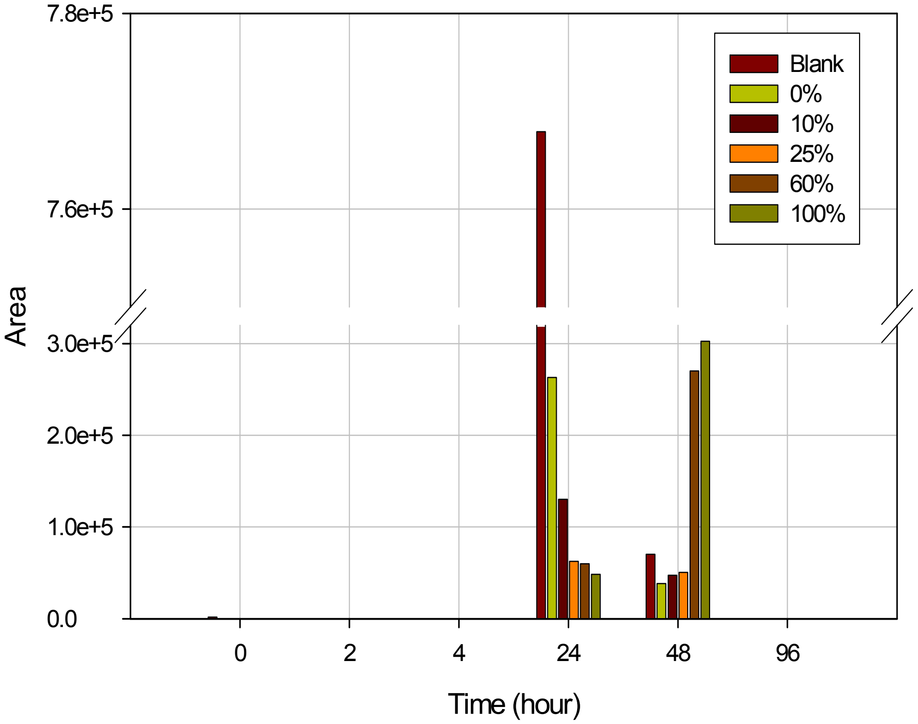


Figure 25: Mercaptan emissions with compost ONA#2

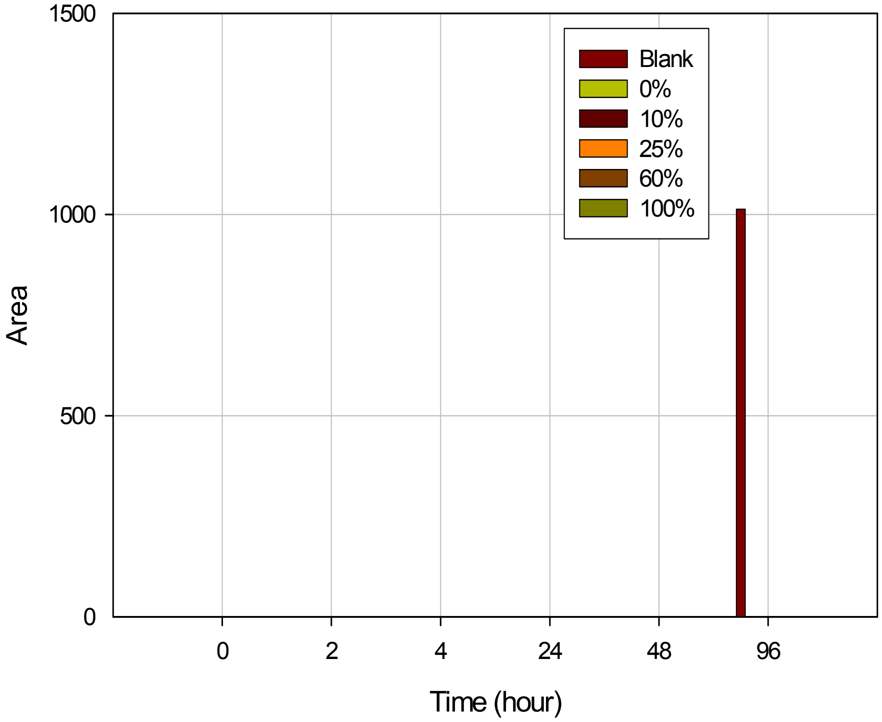


Figure 26: Mercaptan emissions with ORC

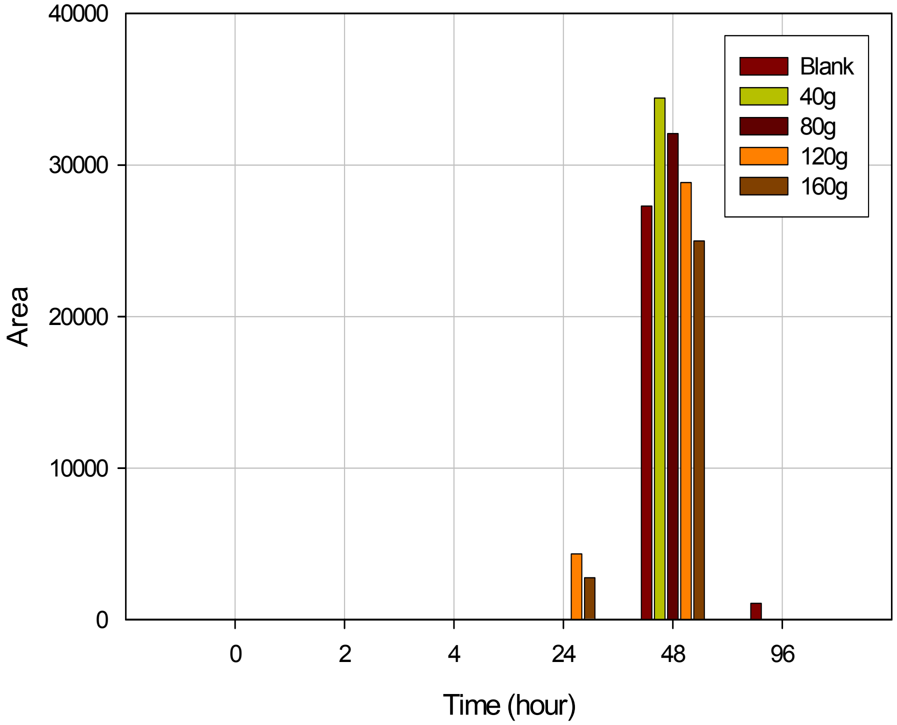
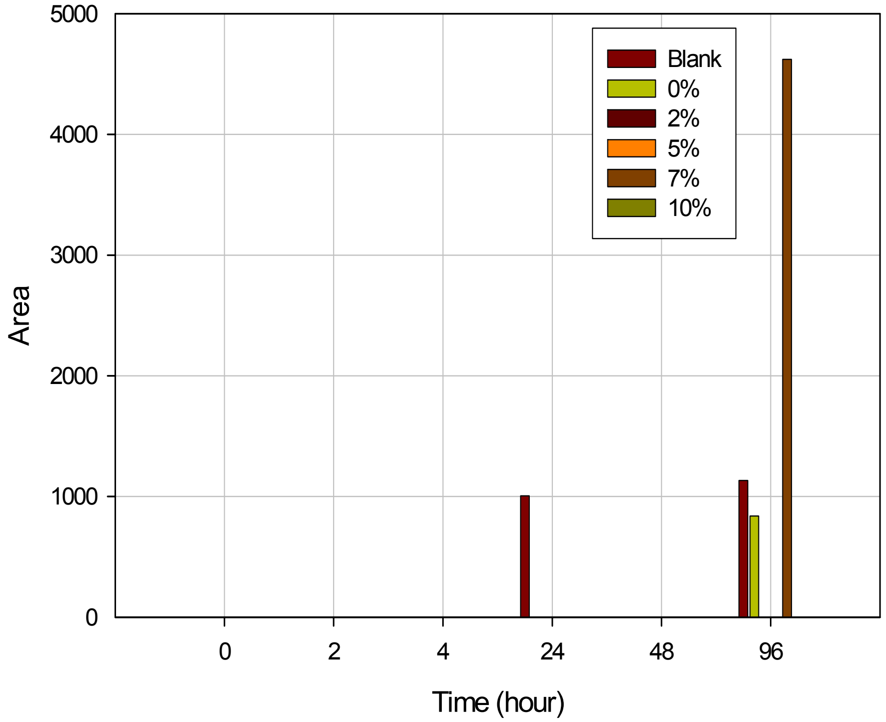


Figure 27: Mercaptan emissions with H2O2



Control of Reduced Sulfur Compounds

Materials

The material was obtained from the Synagro Composting Facility located in Corona, California on the day of experiments. The material was a blend of dewatered biosolids, paper pulp and straw bedding material, and was collected from the inner section of a recently formed composting pile. Up on arrival at the laboratory, the mitigation alternative was applied and the target compounds—mercaptans in this case were investigated.

Analytical Method

Reduced sulfur compounds were captured from the air stream by Orbo-32 (Supelco) 400/200 coconut shell charcoal adsorbent tubes. The contents were extracted by 5-ml of ethylether by a wrist-shaker for 30 minutes. A 1-ml aliquot was taken and transferred into 2-ml amber vials for analysis with a GC-FPD. The analytical method that was followed after extraction was the same as the one for mercaptans. The analytical method efficiencies were reported to be beyond 90% for the tested chemicals.

Results and Discussion

The reduced sulfur compounds were mostly undetectable except for the beginning of the experiment and one point later in the experiment. The results of reduced sulfur compounds are presented in Figures 28 through 33.

Compost Blanket

At the time of application, the compost blanket substantially lowered the total reduced sulfur compounds emission (Figure 27). This reduction, since it was immediate, can be attributed to adsorption of the compounds within the blanket layer. Since, there weren't any significant emissions later in the experiment, the reduced sulfur compounds were probably oxidized over time.

Compost Blend

When compost applied as a part of the blend, the reduced sulfur compounds were noticeable with first day as presented in Figure 28. The incorporation of finished compost resulted in substantially lower reduced sulfur emissions; the higher the amount added, the lower the emissions. Even though, the portion of the fresh feedstock decreased within the blend with increasing finished compost addition, the reductions were beyond the mass effect suggesting that addition of finished compost actually resulted in lower emissions. The most probable mechanisms are adsorption of the compounds by the finished compost and stimulation of biological activity.

Misting and ONAs

The misting and ONAs (there were two studied) didn't yield any conclusive results (Figures 29 through 31). In the misting and ONA#1, the reduced sulfur compounds were generally detectable later in the experiments. Even though, misting and ONA#1 seemed to reduce the amount of emissions at the 48 hours, it is hard to draw a significant conclusion based on a single set of analysis. The ONA#2 results were inconclusive.

ORC

ORC reduced sulfur compounds were identified later in the experiments (Figures 32), and in most cases, the application of the mitigation alternative lowered the amount of reduced sulfur compound emissions. It should be noted that this was the only trial where the application of any ONA had resulted in lower emissions.

Since the composition of the ONAs are not available due to proprietary reasons, it is hard to draw any conclusion in regard to how this reduction might have been achieved. The ORC, as expected, substantially lower the reduced sulfur compound emissions. The reduced sulfur compounds are generated due to development of reducing conditions, i.e. the lack of molecular oxygen, within the compost matrix. Therefore, the release of oxygen from ORC must have prevented the formation of reducing condition.

In most cases, the material had very poor structure. As it was described in the literature review report, volatile compounds escape from the exposed surface. To do so, the compounds must find their way to the surface. Since the material had very poor structure and was almost like mud, it is also possible that the compounds were sealed in. In addition, the material was highly saturated with water.

This would have expected to cause generation of reduced sulfur compound generation due to the hindrance of the aeration. However, the pH analysis of the samples showed that the material were basic (pH>8.5). This could have caused ionization of the reduced sulfur compounds and render them less volatile. Hydrogen sulfide, perhaps other reduced sulfur compounds too, become non-volatile at pH levels above 8 (Das, 2000 and Sawyer and McCarty, 1970)

The issues that were attributed to the materials are discussed in detail later in the conclusion section.

Figure 28: Reduces sulfur compound emissions with compost blanket

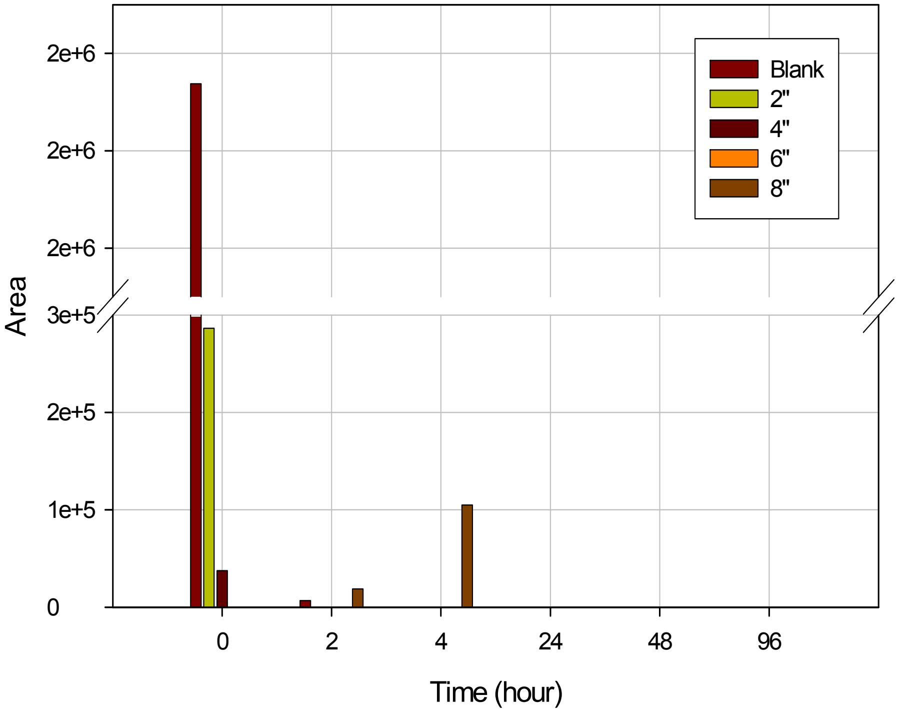


Figure 29: Reduces sulfur compound emissions with compost blend

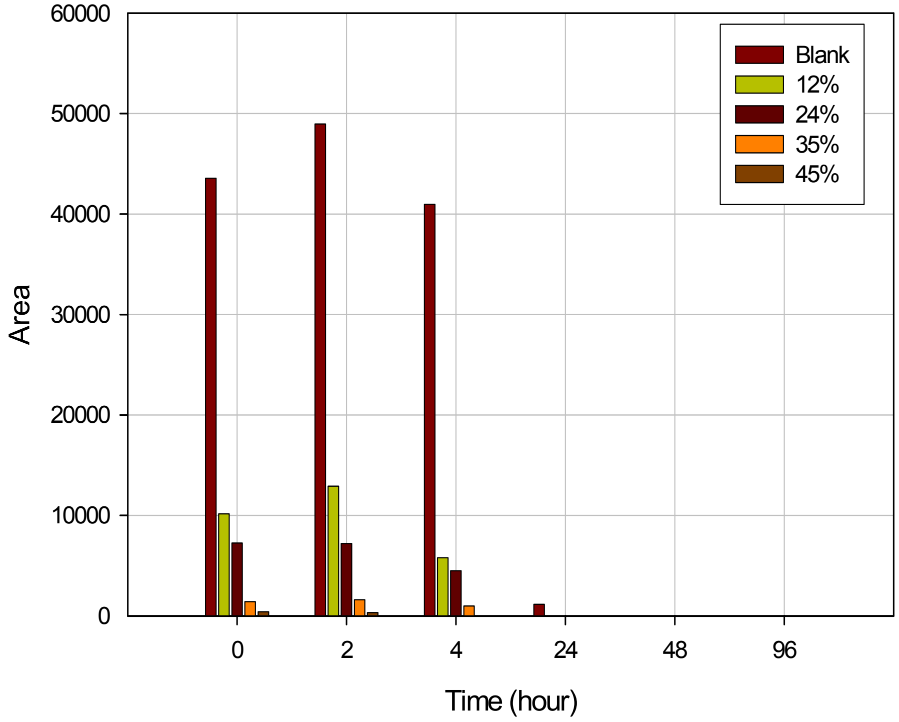


Figure 30: Reduces sulfur compound emissions with misting

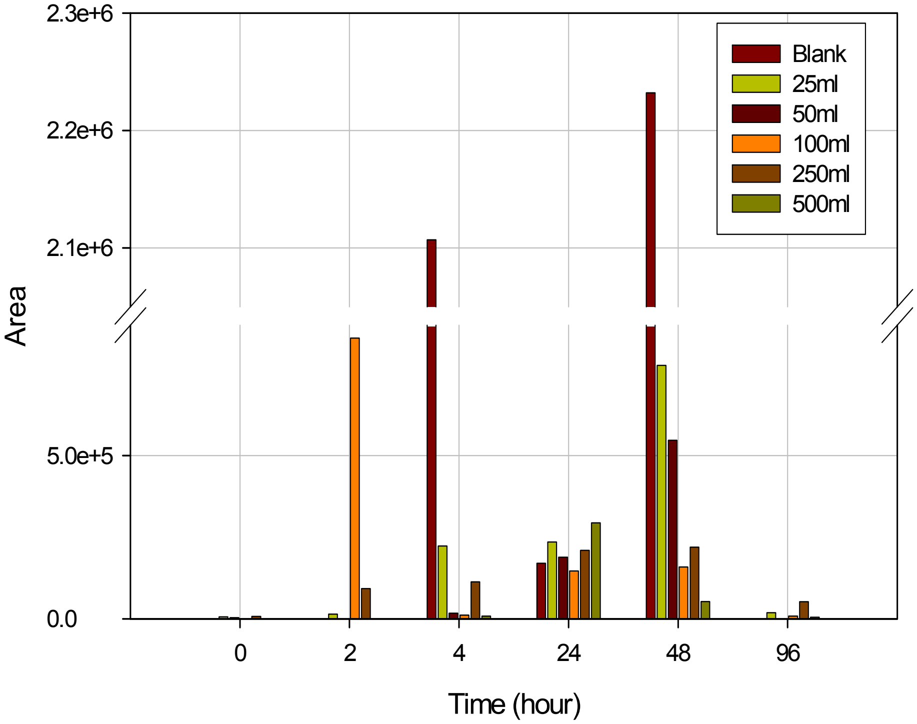


Figure 31: Reduces sulfur compound emissions with ONA#1

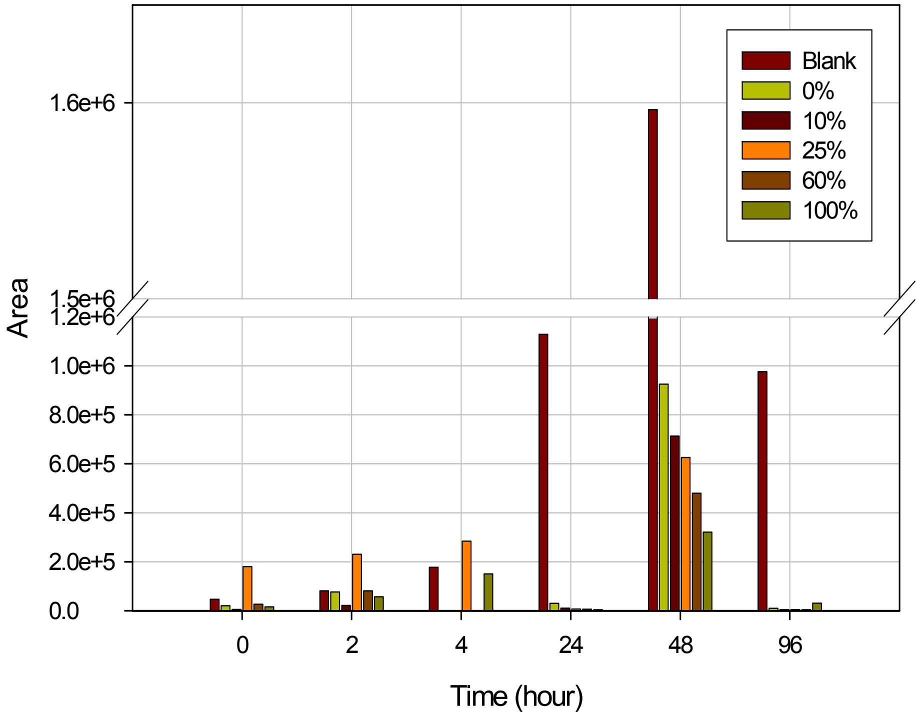


Figure 32: Reduces sulfur compound emissions with ONA#2

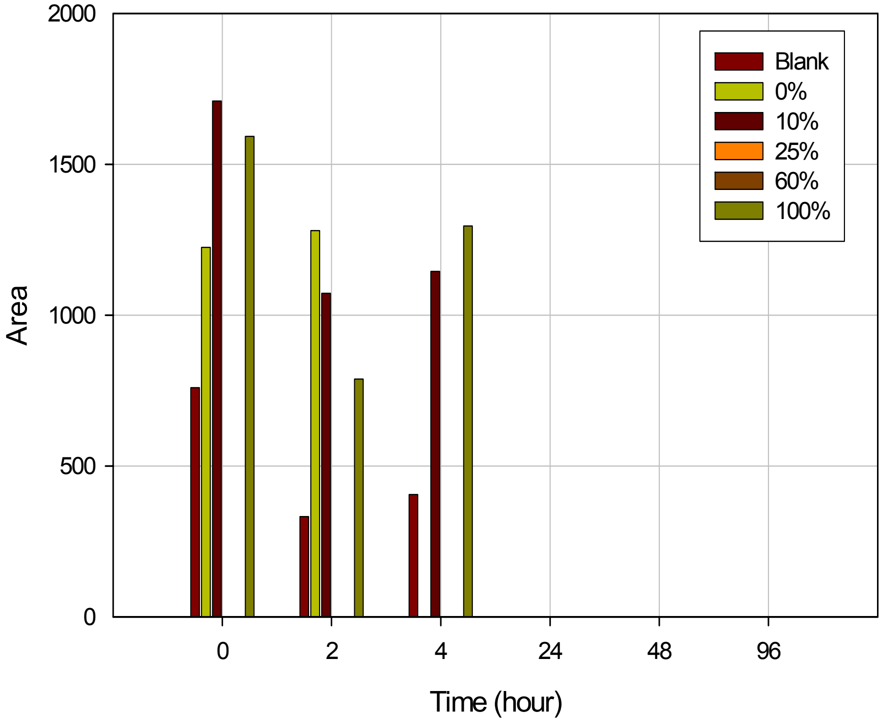
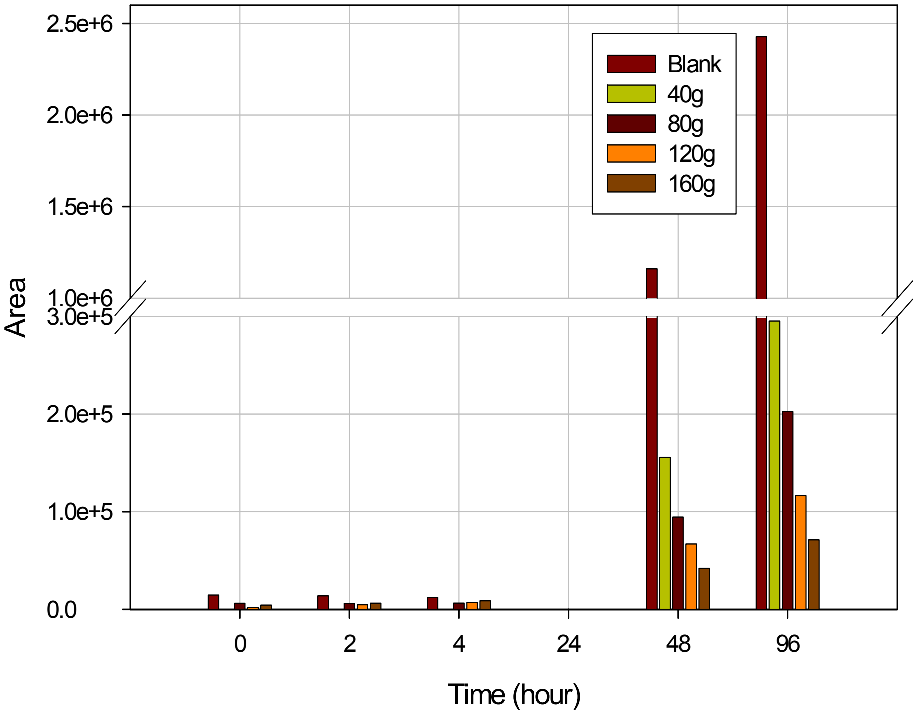


Figure 33: Reduces sulfur compound emissions with ORC



Control of Organic Acids Emissions

Materials

The material was obtained from the Synagro Composting Facility located in Corona, California, on the day of experiments. The material was a blend of dewatered biosolids, paper pulp and straw bedding material, and was collected from the inner section of a recently formed composting pile. Up on arrival at the laboratory, the mitigation alternative was applied and the target compounds—mercaptans in this case were investigated.

Analytical Method

Organic acids were also captured from headspace air stream by Orbo-32 400/200 (Supelco) organic adsorption tubes as described earlier. The analytes were extracted with ethylether for 30 minutes with wrist-action shaker. Extracts were, then, dried and derivatized by a diazomethane, which was generated from Diazald as described by Method AL-180 (Sigma, 2003), to increase the volatility of the parent compounds for GCMS detection. 100 µl of dioazomethane was combined the dried vial and vortexed to ensure reaction completeness; then, it was combined with 300 µl of ethylether and 10 µl of 4,4'-dibromooctafluorobiphenyl, as internal standard for quality control. The derivatized samples were then analyzed by a GC-MS by a method, which was based on Standard Methods 6251.

A 2 µl of sample was introduced to the GC-MS. The injector and and detector temperatures were maintained at 160°C and 300°C, respectively. The column was initially maintained at 37°C for 21 minutes and then ramped to 136°C at a rate of 11°C/min, and maintained for 3 minutes. It was, then, increased to the final temperature of 236°C at a rate of 20°C/min and kept at this temperature for 3 more minutes. The method efficiencies were determined to be 82.6, 94.2 and 73,6% for acetic, butyric and propionic acids, respectively.

Results and Discussion

None of the odor mitigation strategies studied resulted in any improvement for organic acid emissions as presented in Figures 34 through 40. The level of organic acid emissions stayed fairly constant for every run regardless of the mitigation alternative applied to it. The pH analysis reveled that the pH of the feedstock was above 8.5 for all materials. At this pH, the organic acids would ionize and become nonvolatile. The amount of organic acids detected from the fresh material was very close to the emissions from finished compost in most cases. As explained above, this was attributed to the pH of the media. Further discussion of material related issues is provided within the Conclusion section.

Figure 34: Organic acid emissions with compost blanket

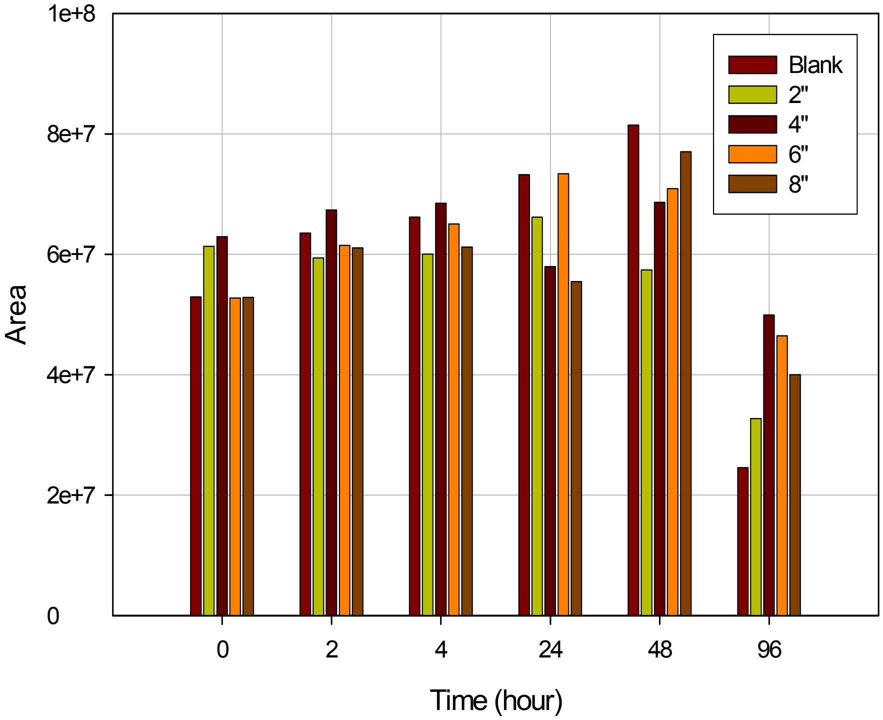


Figure 35: Organic acid emissions with compost blend

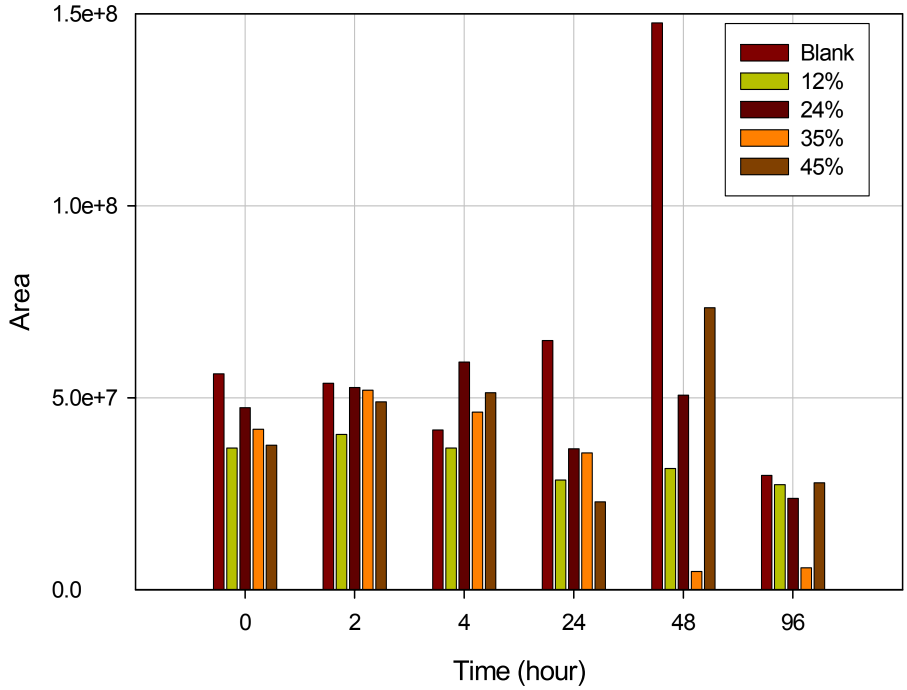


Figure 36: Organic acid emissions with misting

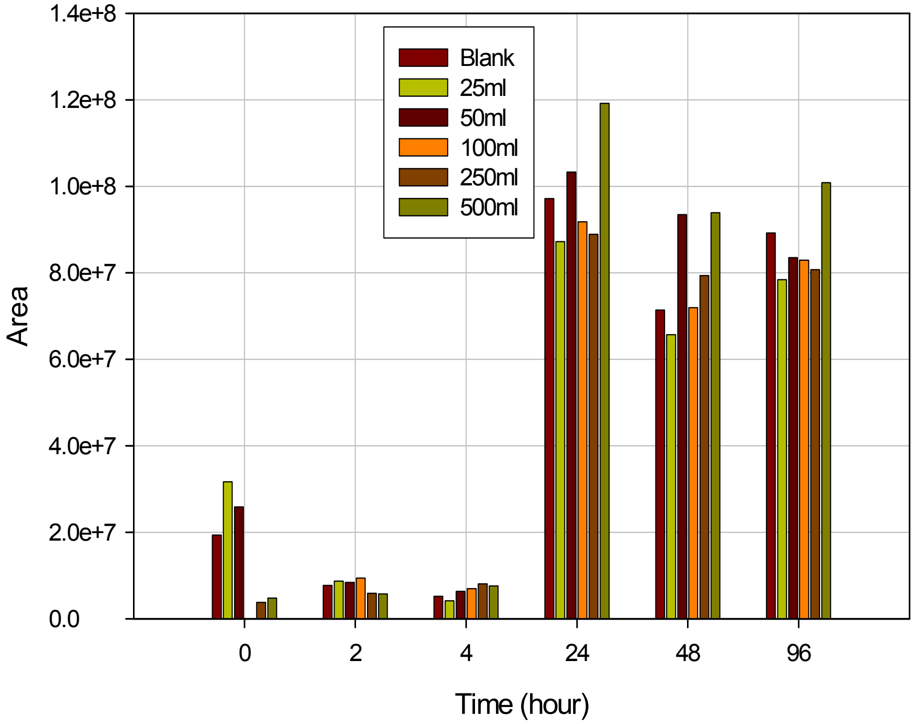


Figure 37: Organic acid emissions with ONA#1

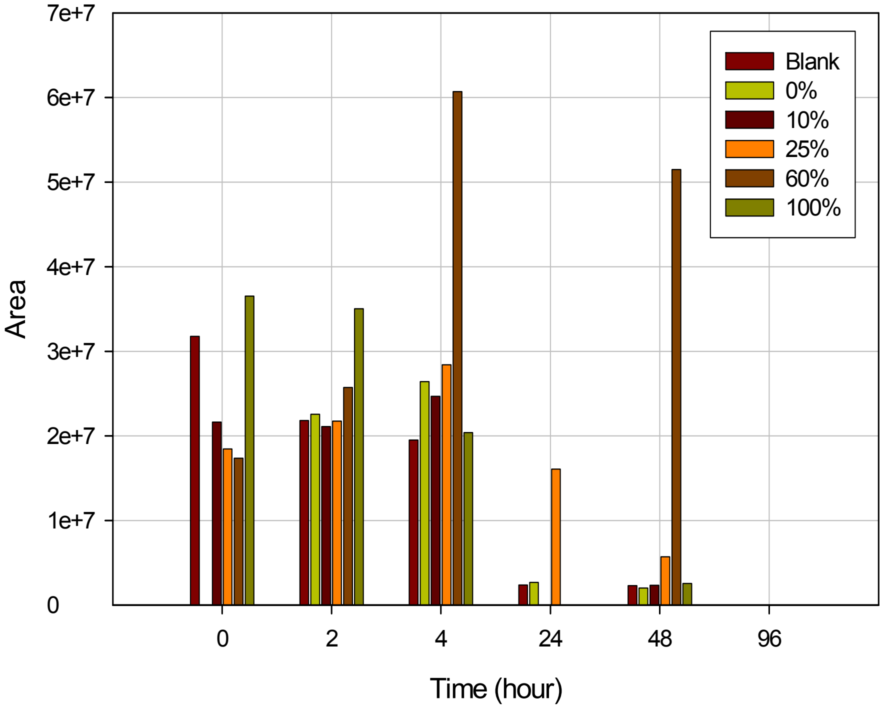


Figure 38: Organic acid emissions with compost ONA#2

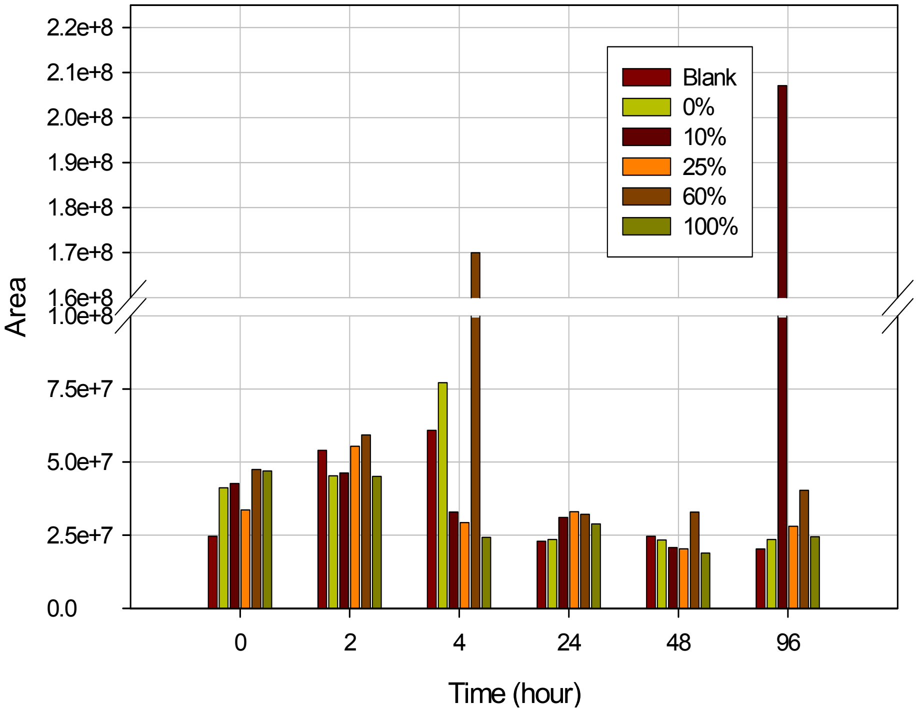


Figure 39: Organic acid emissions with compost ORC

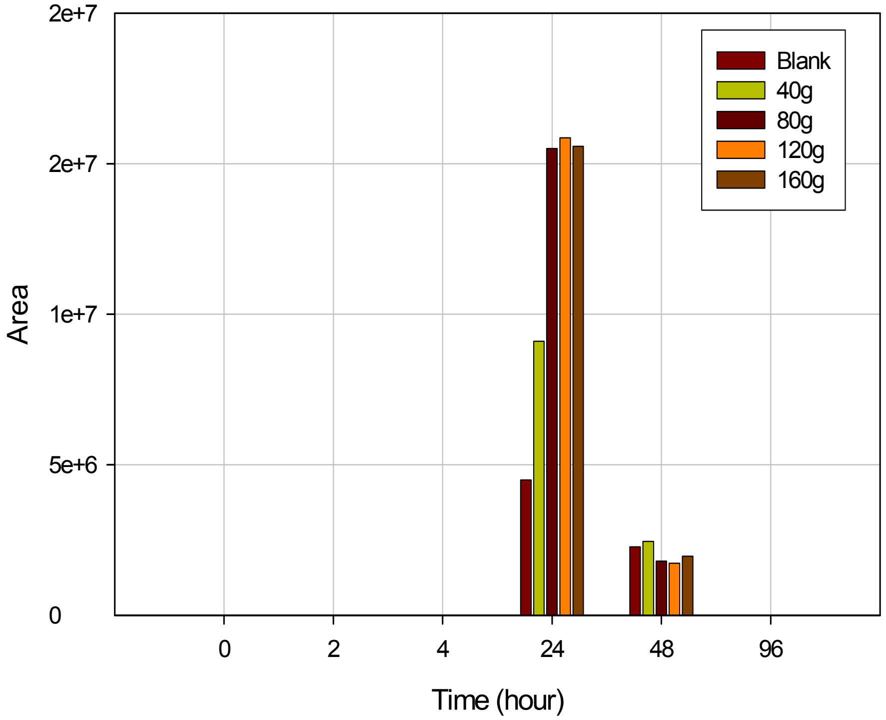
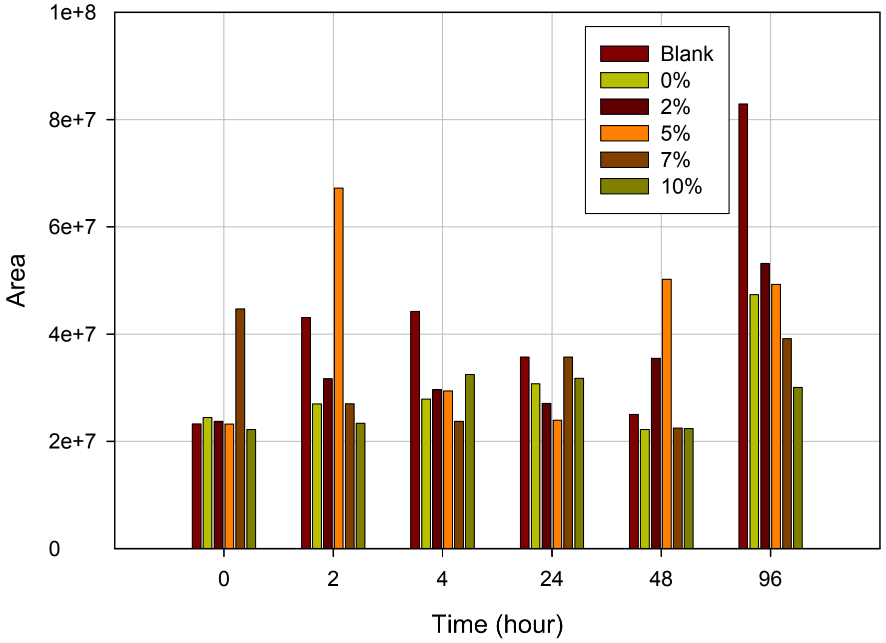


Figure 40: Organic acid emissions with H2O2



Control of Other Organic Compound Emissions

Materials

The material was obtained from the Synagro Composting Facility located in Corona, California on the day of experiments. The material was a blend of dewatered biosolids, paper pulp and straw bedding material, and was collected from the inner section of a recently formed composting pile. Up on arrival at the laboratory, the mitigation alternative was applied and the target compounds—mercaptans in this case were investigated.

Analytical Method

VOCs were trapped by the same Orbo®-32 400/200 adsorption tubes and extracted with ethylether as previsously described for sulfurous compounds. 1-ml of the extract was placed in amber autosampler vials and combined with 10µl of internal standard (4,4'-dibromooctafluorobiphenyl) and analyzed by a GC-MS using the same method that was used for the organic acids.

Results and Discussion

None of the samples analyzed in any treatment resulted in any peak except for the internal standard and several siloxane compounds that are result of typical column spitting. Therefore, the results are not provided here. This phenomenon is attributed to the issues related to the materials used in this study. Further discussion of material related issues is provided within the Conclusion section.

Conclusions

Among the mitigation alternatives investigated in this study, the use of finished compost as a blanket and part of the blend yielded the most conclusive and significant results. For terpenes, ammonia and reduced sulfur compounds, both of these alternatives yielded a substantial emission reduction. However, neither the blanket nor the inoculum results were inconclusive for mercaptans largely since they were not found in most samples.

Both mitigation alternatives seemed to be ineffective in reducing the organic acid emissions; however, it is important to note that it was observed that both the feedstock and the finished compost emitted similar levels of organic acids. Therefore, the use of compost blanket and blend should not be viewed as infective; but rather the feedstock has not resulted in organic acid emissions more than the finished compost.

It is also important to note that the use of compost blanket and compost blend deserves a special attention. That is because the finished compost as a part of the blend describes the situation after a turning event when finished compost was used as blanket. The results clearly suggest a continued reduction effect even after finished compost blanket gets incorporated with the pile after a turning event.

Misting was found to be ineffective for control of terpene and organic acid emissions. It had a negative impact for ammonia emissions at low application rates, yet considerably lowered the emissions at high application rates (beyond 2.5 L/m^2).

Odor neutralizing agents yielded results that were either non-effective or inconclusive, except for ONA#1 for control of reduced sulfur compounds. In this case, this particular ONA seemed to be effective in controlling emissions beyond two days.

Oxygen release compound was effective in reducing the emissions of reduces sulfur compounds while it was ineffective for organic acids. It had a negative impact on ammonia emissions. Hydrogen peroxide was tested for sulfur compounds and organic acids; and data was inconclusive.

Several of the targeted compounds were not generated by the tested feedstock. There were several observations made that we believe might have caused this. In most cases, the material was saturated with water due to intense precipitation throughout this study.

It is commonly accepted that saturated compost material would cause generation of malodorous compounds. However, at the time of collection, material was almost free of odor. Even the vicinity of the facility was free of odors compared to the sunny days. Our further investigation revealed that material was basic (pH>8.5), this would cause many of the target chemicals such as hydrogen sulfide, mercaptans and organic acids to ionize and render them less volatile. The cause of the high pH conditions could be attributed to paper pulp and/or lime stabilized biosolids.

Furthermore, the material had very poor structure—it had a muddy-like appearance in most cases. This could have also sealed the surface and block the flux of chemicals; thus, cause entrapment of the compounds within the pores of the material and get decomposed. In addition, as described in the *Literature Review* section, most of the emissions in a windrow or passively aerated composting system results from the flux of air created by the temperature profile. As the temperature in the inner parts of the compost matrix heats up, the warmed air rises up with the (odorous) compounds, and causes the emissions from the surface. The size of the experimental containers might be insufficient to generate enough heat to cause the flux of air.

The readers, as described earlier, are cautioned not to rule out any odor mitigation alternative based on the results of this study. In many cases the targeted odorous compounds were not generated. Therefore, the efficacy of the mitigation alternative could not be measured. It was concluded that the blend of materials—biosolids-paper pulp-bedding, used in this study might not suitable for all target compounds. However, due to the time limitations and hardship of obtaining desired materials on a consistent base, the change of the experimental design was not possible.

For future studies, we suggest the following should be considered:

- The sampling of headspace air should start immediately after the application of mitigation alternative.
- The use of alkaline materials, such as lime-stabilized biosolids, should be avoided since it renders a large number of odorous compounds non-volatile.
- The scope of the work should be simplified; the study should be performed on a full-scale. The mitigation alternatives might be applied at only one or two levels that would allow the testing on full-scale.
- An *odor panel* should be employed when performed on full-scale.

Table 11: Summary of mitigation alternatives research

Chemical Class	Blanket	Blend	Misting	ONA#1	ONA#2	ONA#3	ONA#4	ORC	H_2O_2
Terpenes	E	E	N	N	N	N	N	N/A	N/A
Ammonia	E	E	E*	I/C	I/C	N/A	N/A	Neg.	N/A
Mercaptans	I/C	I/C	I/C	I/C	I/C	N/A	N/A	I/C	I/C
Red. Sulfur	E	E	I/C	E**	I/C	N/A	N/A	E	N/A
Org. Acids	N	N	N	N	N	N/A	N/A	N	N/A

E: Effective; N: Not effective; I/C: In-Conclusive; N/A: Not-Applied; Neg.: Negative effect.

*Misting had a negative impact at low misting rates and it was effective at large application rates.

**It was effective after two days.

LEA Incident Reports

Executive Summary

The complexity of the odor issue at composting facilities necessitates better understanding of various conditions including weather to asses the problem. The *incident reports* filed by LEAs often do not contain such information. Therefore, C-CORP team prepared two additional forms that are proposed for future use. The information gathered by these reports may help better understand the odor issues in future work.

MSDS (Material Safety Data Sheet) Forms

The Material Safety Data Sheet forms of the compounds used in preparation of odor vials are available at ciwmb.ca.gov/Publications/Organics/Extracts/44207001/MaterSafety.pdf. It should be noted that the MSDS forms are given for high purity chemicals. For instance, the MSDS form for cadaverine is provided for 98% purity; whereas, the concentration of cadaverine in vial is only 0.05% (500 mg/L). Therefore, the toxicity and adverse effect data provided on the MSDS forms are not comparable to the contents of the vials. MSDS forms are provided as a reference only.

Odor Incident Assessment Criteria

As a sub-component of the C-CORP project, the C-CORP team drafted two "model" forms for gathering data related to odor incidents from composting facilities. These forms are intended to provide guidance to LEAs, the CIWMB and compost facility operators for collecting data that can help identify the factors contributing to odors, and consequently the measures that can be used to mitigate the odors. These forms, or derivatives of them, might be useful the following purposes:

- To investigate or troubleshoot a current odor incident (troubleshooting, not necessarily to verify complaints)
- To determine the possible causes and factors of odor incidents that have already passed, (e.g. no longer on the LEA's desk)
- To collect data for a data base to generally assess the nature, cause and cures for odors at composting facilities (perhaps more of an academic purpose)

The two forms are provided here are: (a) an odor incident investigation report (OIIR); (b) and an odor assessment form (OAF). Each of the forms lists a menu of possible factors influencing the generation and release of malodors at composting facilities.

(A) The OIIR was developed as a model data collection device for determining the cause of a specific odor incident. It could be used as a complement to the odor complaint form current used by LEAs (e.g. the CIWMB's "Enforcement Agency Complaint Form," which is also provided here for comparison). An LEA, or any other professional user, can adapt the form to suit their preferences and situations.

(B) The OAF form is more of a research tool. It was developed for gathering a variety of odor-related data about the character of individual facilities. After this data is collected from numerous facilities it can be evaluated in relation to each facility's odor history to indicate what factors and conditions lead to odors generally. Such an analysis could be a more rigorous follow-up of the odor preliminary odor assessment of composting odors, as suggested on the previous component of this project.

The forms are models only in a suggested sense. They provide a starting point to be adopted, adapted and modified to suit the needs, preferences and situation of the user. They can be and should be freely altered. Considering that both forms are intended to be modified by the user, they are purposely detailed and comprehensive in identifying factors, conditions and information that might be collected and considered. The user can delete unnecessary items in order to make the form more manageable.

The forms consider several categories of information:

- General
- Feedstocks
- Process
- Management
- Site
- Community
- Meteorological
- Time and nature of complaints

Specifically the categories and items on the forms are included to answer the following questions about odor incidents:

- Are odors mostly caused by the nature of the raw feedstocks (i.e. type and condition)?
- Are odors mostly caused by process conditions (e.g. anaerobic piles, turning, porosity)?
- Are odors caused by simply having too much material in one place? (e.g. volume/acre)
- Does the site itself emit odors? (e.g. surfaces imbued with the essence of organics)
- Are odors a result of poor management? (e.g. too few employees, too little oversight, growing pains)
- Are odor complaints largely a weather phenomenon? (e.g. temperature inversions, wind direction, rain)
- What role does topography play? Is it better to be on the hill or in the valley?
- Are odor complaints primarily an issue of distance and direction?
- How much are odor complaints determined by sociological factors? (e.g. a tainted history in the community, a few angry antagonists, empowered neighbors, property values, non-agricultural neighbors)
- What combinations of the above are most at work? Are most important?

ODOR INCIDENT INVESTIGATION REPORT (OIR)

Note: This is not intended to be an "inspection" report per se (to indicate the regulatory agent's verification of the odor). It is more of an evaluation to determine the cause of the odor incident.

GENERAL Date: _____________

Facility Name: ____

Address: ____

Town: _________________, State: _______, Zip code: ___________ County: __________

Facility contact: ____

Phone: ____

Email: ____

Regulatory jurisdiction: ____

Regulatory contact: ____

ODOR COMPLAINT:

Nature of the complaint: ____

Date of 1st complaint: ______________ Day of week: ____________

Time(s) during day: ____

Source of Complaint(s):

___ Residence ___ School ___ Business ___ Vehicle

Other: ____

Odor character: ___ Pungent ____ Rotten ___ Putrid ___ Other ________

Intensity ___ Strong ___ Strong-mild ___ Mild ____ Faint

Consistency: ___ Constant___ Irregular/consistent___ Irregular/sporadic ___ Rare/brief

Duration of incident: _______________ hours

Time of day first detected _________________

Time of day no longer apparent: ___________________

Location(s) where odor detected:

Direction from facility (circle all that apply): N NE E SE S SW W NW

Distance to nearest complaint: ________ ___ Upslope or ___ down slope?

Distance to FURTHEST complaint: ________ ___ Upslope or ___ down slope?

Facility and Community history

Previous complaints for site: __ Many __ Occasional __ Few __ None

Previous complaints by complainant(s) __ Many __ Occasional __ Few __ None

SITE CONDITIONS AT TIME OF COMPLAINT

Feedstocks generally handled : ____

Feedstocks received on day of complaint and/or previous day:

Material	Day	AM/PM	Condition

Activities on day of complaint and/or previous day:

Activity (e.g. turning, pile moved, delivery)	Day of Week	AM/PM

Extraordinary circumstances

(e.g. spill, equipment breakdown, employee incident, odorous load, etc.):

Resolution of the above:

APPROXIMATE WEATHER CONDITIONS (e.g.warm, hot, windy, sunny, light rain, etc)

	At time of 1st Previous	Morning of Same	Afternoon of Same	Previous

	complaint	Day	Day	Afternoon	Night
Temperature	____________ ____________ ___________		____________ ____________		
Cloud cover	____________ ____________ ___________		____________ ____________		
Prevailing wind	____________ ____________ ___________		____________ ____________		
Wind conditions	____________ ____________ ___________		____________ ____________		
Precipitation	____________ ____________ ___________		____________ ____________		
Humidity	____________ ____________ ___________		____________ ____________		

Unusual weather conditions (e.g. very strong wind, temperature inversion):

____

____

____

Description of weather character for previous five days (e.g. hot and humid for 3 days followed by heavy rain and mild temperatures):

____

____

____

ODOR ASSESSMENT FORM (OIA)

GENERAL:

Facility: ____ Date: ______________

State: ________ County: ________________ Town: ___________________

Facility contact:

____

Conatct Information: ____

Regulatory jurisdiction: ____

Regulatory contact: ______________________________

Type of facility:

- ___ Public (circle: municipal county other)
- ___ Private
- ___ Public/private combination
- ___ Institutional (circle: university prison park other)
- ___ Farm
- ___ Other: ____

Feedstock Category: (green waste, biosolids, manure, MSW, other):

____

FEEDSTOCKS (AROUND THE TIME OF ODOR INCIDENTS):

Approx. Condition When Received

Material Percentage (e.g. wet, well mixed, anaerobic)

Primary _______________ _____ %
____

Secondary _______________ _____ %
____

Third _______________ _____ %
____

Fourth _______________ _____ %
____

Other additives:
____

Feedstock Sources (rank, from most to least)

___ Generated on site:
___ From transfer station Distance: __________
___ From storage facility Distance: __________
___ Direct collection from single generator Distance: __________
___ Direct collection from multiple generators Longest/shortest Distance: _______
___ Delivered by multiple generators (e.g. public)

Amount of Material on site

Raw feedstocks: _________________________ tons or cubic yards
In process: _________________________ tons or cubic yards
Curing compost: _________________________ tons or cubic yards
Finished compost: _________________________ tons or cubic yards

Average throughput: ________________________ tons or cubic yards per day, week or month

Growth in feedstock capacity

_____ % in past 2 years

_____ % in past 5 years

_____ % in past 10 years

PROCESS:

Target C/N ratio:

Target moisture content:

Composting method:

Typical windrow/pile/vessel dimensions:

Approximate turning schedule:

Turning equipment

Aeration rate: ____

Aeration strategy: (positive, negative, continuous, intermittent, timer control, temperature feedback)

Composting period:

Stage 1: _______ days

Stage 2 (or curing): _______ days

Bilofilter:

Media:

Dimernsions:

Air flow:

Chemical treatment: Type: ______________

Additional Operations	Equipment	At What Stage in Process
Mixing/blending:	________________________	_________________
Grinding:	________________________	_________________
Screening:	________________________	_________________
Bagging	________________________	_________________
Other:	________________________	_________________

MANAGEMENT

Number of employees (FTEs --full time equivalent): __________________

Supervision by:	% Time devoted to the composting facility
Owner	________________________________
Manager	________________________________
Operator	________________________________
Other: ________________________	________________________________

Facility Operation schedule:	Days per week	Hours per day
Feedstocks accepted:	______________________	_______________
Equipment operated	______________________	_______________

Operation schedule restrictions:
____

Odor Management Plan: Yes No Author: ________________________

Facility Operation Plan: Yes No Author: ________________________

Composting Parameters Regularly Monitored	Monitoring Frequency	Monitoring Method
___ Temperature	________________	______________________
___ Moisture	________________	______________________
___ Oxygen	________________	______________________
___ Odor	________________	______________________
___ Other: ___________	________________	______________________

Odor Control measures in place: _______________________________________

____
__

___ Odor neutralizing chemicals; Product: __________________

___ weather station ___ wind sock

SITE CONDITIONS AND FEATURES

Area of entire site (active operation): ______________________________ acres sq. ft.

Area of composting pad: ______________________________ acres sq. ft.

Area of curing pad ______________________________ acres sq. ft.:

Area of feedstock storage areas: ______________________________ acres sq. ft.

Composting pad slope:

Composting pad surface:

Road surface:

General site surface:

Site maintenance rating: excellent, good, fair, poor, terrible

Site appearance rating: excellent, good, fair, poor, terrible

Enclosure/Cover: (check)

Process Stage	Open	Membrane or Blanket Cover	Roofed Structure	Fully Enclosed
Feedstock receiving	___	___	___	___
Feedstock storage	___	___	___	___
Amendment storage	___	___	___	___
Composting – stage 1	___	___	___	___
Composting stage 2	___	___	___	___
Curing	___	___	___	___
Compost storage	___	___	___	___
Grinding area	___	___	___	___
Screening area	___	___	___	___
___________________	___	___	___	___
___________________	___	___	___	___

Stormwater management:

___ Retention pond: Dimensions: _________________________________

___ Direct discharge: To: ____

Site Topography:

___ On top of hill ___ On slope of hill: Grade: ______ %

___ In valley ___ In "bowl"

General land use of site:

___ Farm, ___ Landfill, ___ Gravel pit, __ Industrial land, __ Commercial land,

Zoning: ____________________________

Visibility:

From public road: Fully visible, partially, slightly not visible

From neighboring residences/buildings: Fully visible, partially, slightly not visible

Comments:

____

Buffer Area

	Buffer Area land use	Width	Neighboring land use
North	___________________	________	_____________________
East	___________________	________	_____________________
South	___________________	________	_____________________
West	___________________	________	_____________________

Distance to nearest neighbors

	Neighborhood Character (residential, commercial, mixed)	Distance from Site Border	Elevation Change (++, +, 0, -, --)
North	______________________________	___________	____________________
East	______________________________	___________	____________________
South	______________________________	___________	____________________
West	______________________________	___________	____________________

Other Possible Sources of Odors in Vicinity (e.g. farms, factories)

Source	Distance from site
____	___________
____	___________
____	___________
____	___________

METEORLOGICAL

Nearest official weather station: ___________________

Approximate annual precipitation: _______________

Precipitation pattern (e.g. seasonal, uniform, snow): ___________________

Temperature and wind speed:

	July	January
Average High Temp	__________	____________
Average Low Temp.	__________	____________
Average Wind Speed	__________	____________

Normal wind conditions: (check)

	Winter	Spring	Summer	Autumn
Frequent and steady:	______	______	_____	_____
Frequent and gusty	______	______	_____	_____

Infrequent	_______	_______	_______	_______
Sporadic and irregular	_______	_______	_______	_______

Wind direction:

	Generally	Winter	Spring	Summer	Autumn
% time from North:	_______	_______	_______	_______	_______
% time from East:	_______	_______	_______	_______	_______
% time from South:	_______	_______	_______	_______	_______
% time from West:	_______	_______	_______	_______	_______

Temperature Inversions: (check)

	Generally	Winter	Spring	Summer	Autumn
Frequent:	_______	_______	_______	_______	_______
Infrequent:	_______	_______	_______	_______	_______

COMMUNITY PROFILE

Community Character: (check all that apply)

___ Rural; ___ Rural/suburban; ___ Suburban; ___ Urban

___ Growing rapid ____ Steady growth; ___ Little growth or decline

___ Agricultural; ___ Forested ___ Dessert/range

Comments:

____

Town population: __________________; ____________ % growth (past 5 years)

County population: ____________________; ______________ % growth (past 5 years)

Median town (or county) income: ___________________________

Waste Services: (check predominant service)

Wastewater: ___ Individual ___ Community ___ Municipal

MSW collection: ___ Self haul ___ Municipal collection Private collection

MSW disposal: ___ Landfill ___ Incineration ___ Other: ____________

Yard trimmings banned from landfill? ___ Yes ___ No

Burn ban? ___ None ___ Trash ___ Green waste

Other odor sources in community: (check all that apply)

___ Landfill

___ Wastewater treatment facility: Type: ________

___ Poultry farm

___ Swine farm

___ Dairy or cattle feedlot

___ Mushroom farm

___ Food processing factory

___ Other industry, Type: _________________

Neighbor relationships: Cordial Courteous Tolerant Contentious

Community relationship Cordial Courteous Tolerant Contentious

Composting facility/community partnership:

___ Neighbors review facility plans

___ Neighbors/community official monitors

___ Neighbors/community advise facility

Facility complaint history:

Average number of complaints per year (past 5 years): ________

Number of complaints last year: ____________

Number of complaints past 6 months: _____________

Time since previous complaint: _____________ days

Mitigation Strategy Menu

Mitigation Strategy Menu Detailed Explanations

The Odor Mitigation Strategy Menu (OMSM) is a comprehensive listing of possible design and operating techniques that can be used to prevent and minimize odors from composting facilities. The OMSM is designed to be used in concert with the odor identification kits, the odor incident survey forms, and the odor matrix. The following shows how the OMSM fits in with the other C-CORP tools.

Odor Incident Survey Forms

⇓

Odor Matrix

⇓

Odor Mitigation Strategy Menu

⇓

Odor Mitigation Strategy Menu Explanations

The OMSM conceptually breaks down each process step at a composting facility into a discrete area with discrete odor potential. Each processing area contains a number of mitigation strategies to reduce odors from that particular area. This approach is critical to a scientific assessment of odor problems and resolution.

Mitigation Strategy Menu Detailed Explanations

The following provides explanations of the management practices listed in the C-CORP Mitigation Strategy Menu.

1.0 MATERIAL RECEIVING

1.1 Material Arrives with Odors:

Some feedstocks, because of their nature or because of collection practices, will arrive at a facility in an odorous state. The following mitigations may reduce the potential for these odorous compounds to become a problem.

1.1a Mix materials offsite before receipt (if possible).

Add sawdust to chicken manure before shipping to compost offiste.

1.1.1 Mix materials upon receipt (increase material porosity):

Highly degradable feedstocks, like food waste, can be managed by immediately incorporating the degradable materials into a pile of already composting woody materials (like green material or wood chips) to increase their porosity and to facilitate the biological process. Scheduling deliveries of highly degradable materials and being prepared for them can reduce the potential for off-site odors.

1.1.2 Stockpile bulking agent or high carbon amendments as receiving basin:

Some feedstocks, like biosolids, food wastes, liquid wastes, etc. are best handled by creating a receiving basin. A receiving basin (often laid out like a horseshoe), allows rapid incorporation of a bulking material into a feedstock that needs it. This helps establish porosity and facilitates the beginning of the biological process. Appropriate bulking agents/amendments include wood chips, woody overs, straw, etc.

1.1.3 Stockpile bulking agents or high carbon amendments for unexpected deliveries:

If deliveries cannot be scheduled, a pile of appropriate bulking materials could be stockpiled in anticipation of deliveries of highly degradable materials. Appropriate bulking agents/amendments include wood chips, woody overs, straw, etc.

1.1.4 Make smaller piles:

Making smaller piles (storage piles, or windrows) increases the ability of natural aeration processes to bring air into a pile (limit to 10 feet or less). Creating discrete piles (of different feedstocks, like dimensional lumber versus green material) allows you to isolate highly degradable materials from relatively more stable ones and manage accordingly. Process stored materials promptly.

1.1.5 Consider blanketing odiferous materials with a six-inch to one-foot layer of bulking agent, high carbon amendments, or finished compost, (water lightly to reduce odor releases):

Research (Büyüksönmez, 2006) has shown that providing a "pseudo-biofilter" or a blanketing layer of finished compost over composting materials reduces the odorants being emitted from the composting materials. The same effect can be achieved by blanketing incoming materials with finished compost or other organic materials. Some facilities have used woody "overs" the oversize woody pieces screened out of finished compost to provide this same blanketing effect. Watering the "blanket" materials allows more odorants to be absorbed onto the woody particle.

1.1.6 Enclose the receiving floor:

To reduce passive emissions put receiving floor in a building that allows capture and treatment of emissions.

1.1.7 Aerate receiving floor:

Some composting facilities in sensitive areas that regularly receive highly degradable feedstocks have added negative aeration to their receiving areas. This is typically done inside of a building with aeration piping being set into the receiving floor.

1.1.8 Add lime or wood ash to piles to adjust pH:

If the material has a low pH (below 6) and volatile organic acids or hydrogen sulfide or mercaptans are detected, adjust pH upward by adding lime, wood ash or other alkaline materials.

1.1.9 Reject odorous loads if possible:

If the facility is not set up to handle odiferous loads, the scale-house operator could perform an odor assessment and reject particularly smelly loads.

1.1.10 Eliminate troublesome feedstocks:

Some feedstocks are inherently odorous and can cause problems at some facilities. Grass, grease trap waste, septage and other highly putrescible materials may not be appropriate for all sites at all times. If possible, eliminate these feedstocks from the mix to reduce odors.

1.1.11 Incorporate wet or odorous loads directly into actively composting windrows:

By immediate incorporation, the microbe population already established in an active windrow will immediately begin to attack the odorous compounds. Mixing directly into the windrows establishes the appropriate porosity and reduces the exposure of the material to the environment.

1.2 Material Sitting Too Long Prior to Being Processed or Mixed:

Feedstocks that arrive on site and are not immediately processed can generate odors due to inadequate porosity, inadequate C:N ratio, etc.

1.2.1 Expedite material processing:

By focusing on or prioritizing material processing (grinding, screening, or mixing) a facility can avoid storing feedstocks for undue periods of time.

1.2.2 Increase operating shifts:

One way to deal with preventing material from sitting too long (after a peak loading situation, for example) would be to increase the daily operating shift. However, this must conform to approved operating hours (and depend on the availability of personnel).

1.2.3 Reduce incoming throughput:

By reducing incoming throughput, either by pricing, hours of material acceptance or by otherwise turning away loads is another way to reduce throughput to allow for sufficient time to process all incoming material.

1.2.4 Identify alternative outlets for incoming materials:

If alternative outlets (other nearby facilities) can be identified, that will also ease the pressure on the composting site. In some cases wood and green material could be processed for mulch or boiler fuel or directly land applied rather than being composted.

1.2.5 First in, first out processing:

By processing and/or managing the oldest material on-site first, you can reduce the potential that the older material will release odorous compounds.

1.2.6 Reduce size of material stockpiles:

If circumstances do not allow for efficient and timely processing, reducing the size of the material stockpiles can reduce their potential to emit odors. Reducing surface to volume increases airflow, which generally decreases the potential for odors to be formed.

1.2.7 Increase collection frequency:

Feedstocks which are collected every other week (or less frequently) will likely arrive at the facility with well-developed odors. If possible, increasing the collection frequency will reduce the amount of time the materials are allowed to degrade in a less-controlled manner.

1.2.8 Increase grinding/processing capacity (contract grinder/screener):

If the reason materials are sitting around is lack of processing (grinding, screening, loaders, etc) capacity, processing capacity could be increased either temporarily or permanently. Contracted or leased equipment can help a facility through equipment breakdowns, or temporary spikes in throughput.

1.2.9 Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agents, high carbon amendments, or finished compost, (water lightly to reduce odor releases):

Research (Büyüksönmez, 2006) has shown that providing a "pseudo-biofilter" or a blanketing layer of finished compost over composting materials reduces the odorants being emitted from the composting materials. The same effect can be achieved by blanketing incoming materials with finished compost or other organic materials. Some facilities have used woody "overs" the oversize woody pieces screened out of finished compost to provide this same blanketing effect. Watering the "blanket" materials allows more odorants to be absorbed onto the woody particle.

2.0 GRINDING

2.1 Grinding Volatizes Particles

The act of grinding releases and exposes many volatile particles and exposes them to the open air, promoting volatilization (release) of many odorous compounds.

2.1.1 Add light misting of water or odor neutralizer to grinder at discharge points (along conveyers):

Most, if not all odorous chemicals released during composting are somewhat water soluble. Misting (either with water or a water/odor neutralizer compound mix) can entrain at least some of the odorants as they fall to the ground.

2.1.2 Schedule grinding to coincide with favorable atmospheric dispersion conditions:

First, you need to understand what "favorable atmospheric conditions" are for your site. In general this refers to conditions that would favor dispersal of odorous compounds – typically fairly strong winds, ideally away from the direction of the closest (or most sensitive) receptors. In some cases, it may be easy to predict when conditions are favorable for maximum odor dispersion, in some cases, complex weather situations (like inversions, mixed topography and competing odor sources may make this more difficult to determine. In some cases, favorable dispersion conditions may vary from season to season.

2.1.3 Consider grinding green materials with woodier materials:

In large volumes, grinding green materials by themselves may be sufficient to release enough odor compounds to cause off-site odor nuisances. In these cases, it may be useful to “cut” the volume of green material processed by adding wood wastes (if available). Unfortunately in order to be mechanically (and fuel) efficient, it is typical to grind only when a large pile of materials is accumulated; from an odor release standpoint, it may be better to grind small amounts of materials in intervals, rather than large quantities all at once.

2.1.4 Consider providing redundant equipment to assure on-time processing of delivered materials:

If possible, having redundant equipment available would allow a facility to assure the amount of material received in a given day is also processed that same day, or within scheduled time frames. Having redundant equipment also helps maintain production in the event of an equipment breakdown (a lesser-reported cause of odors at composting facilities).

2.1.5 Identify alternative facilities and/or equipment for unexpected deliveries or unexpected equipment failures:

Every facility should identify possible alternative outlets for unexpected or peak deliveries, equipment failure or other unexpected conditions. These can include other nearby composting facilities, biomass facilities, land application sites, or other places where incoming feedstocks can be directed to relieve pressure from the subject facility. In addition, contract grinders can assist during time of equipment failure or major maintenance.

3.0 MIXING/MATERIALS HANDLING

It is important to mix feedstocks promptly to initiate the composting process. Mixing can result in an immediate and intense release of odors. Fortunately they are short-lived. Still, some diligence is required in scheduling and locating mixing activities.

3.1 Mixing volatizes particles and re-invigorates a pile

The act of mixing and/or turning a pile also volatilizes (releases) many volatile particles and exposes them to the open air, promoting volatilization of many odorous compounds.

3.1.1 Create windrows/piles that are sufficiently blended:

Facilities which compost more than one feedstock type need to pay closer attention to thorough mixing of those feedstocks. For example, facilities which accept food scraps in addition to green material should make every attempt to ensure the food scraps are adequately blended with green material. Inadequate blending leads to anaerobic pockets which can cause significant odors. There are readily available spreadsheet programs which can help compost operators manage diverse feedstocks from a carbon to nitrogen ratio standpoint and there is special equipment available for mixing, though the majority of facilities rely on front-end loaders to mix diverse feedstocks.

3.1.2 Combine materials to achieve a high C:N ratio (greater than 30 to 1):

Some feedstocks will benefit from an increased C:N ratio, especially feedstocks prone to releasing organic acids (like food waste). Increasing the C:N ratio may slow the process down, reduce the oxygen demand and help maintain aerobic conditions. With high nitrogen feedstocks, the higher carbon will also slow down the process and preserve nitrogen. In addition, because materials that are high in carbon tend to be bulky and dry, a higher C:N ratio tends to result in a pile with greater porosity and lower bulk density.

3.1.3 Create piles with good porosity:

Passive aeration relies largely on the porosity (free air space) to provide oxygen to the microbes. This is critical to avoid anaerobic conditions and the odors associated with them. One way to do this would be to reintroduce screened overs.

3.1.4 Mixing areas/activities should be located as far as possible from sensitive receptors:

Mixing can result in an immediate and intense release of odors. Locating this area as far as possible from sensitive receptors may reduce odor complaints.

3.1.5 Reduce mixing/materials handling activity during stagnant air conditions:

Stagnant air conditions, typical during temperature inversions, provide the least amount of odor dispersion and can lead to odor complaints, primarily because the air is moving very little or not at all. Although stagnant air conditions typically occur in the early morning or in the late afternoon/evening, inversions can occur anytime under the right conditions. If possible, reducing or eliminating materials handling activities during these conditions will reduce odor transport.

3.1.6 Reduce mixing/materials handling activity when wind is in direction of receptors:

As discussed above, if possible, mixing activities should be scheduled when the wind is in a favorable dispersion direction (away from the nearest receptors).

3.1.7 Enclose the mixing area:

Rapid incorporation of feedstocks is key to reducing odors, therefore it is important to mix materials promptly and get them into the windrow. Enclosing the mixing area may allow a facility to mix feedstocks regardless of wind conditions.

3.1.8 Mist water or odor neutralizer at dust generation points:

Anywhere that dust is generated, odor is also likely generated. Most, if not all odorous chemicals released during composting are somewhat water-soluble. Misting (either with water or a water/odor neutralizer compound mix) can entrain at least some of the odorants as they fall to the ground.

4.0 COMPOSTING

4.1 Less than ideal conditions can form odorous compounds

Many techniques for reducing odor at composting facilities relates back to the basics of good composting practice: balanced carbon and nitrogen in feedstocks, good porosity, sufficient moisture content, etc.

4.1.1 Reduce turning and/or material handling activity during stagnant air conditions:

Stagnant air conditions, typical during temperature inversions, provide the least amount of odor dispersion and can lead to odor complaints, primarily because the air is moving very little or not at all. Although stagnant air conditions typically occur in the early morning or in the evening, inversions can occur anytime under the right conditions. If possible, reducing or eliminating materials handling activities during these conditions will reduce odor transport.

4.1.2 Reduce turning/material handling activity when wind is in direction of nearby receptors:

As discussed above, if possible, turning or other material handling activities should be scheduled when the wind is in a favorable dispersion direction (away from the nearest receptors).

4.1.3 Turn regularly to reinvigorate the composting process:

Turning introduces air and improves the distribution of moisture, nutrients, and microorganisms and generally invigorates the compositing process. Depending upon the materials and their stage of composting, turning may or may not improve porosity. In any case, regular turning advances the composting process and minimizes the accumulation of anaerobic by-products.

4.1.4 Maintain sufficient moisture in windrows:

Although at first, a lack of moisture content in a windrow will not lead directly to the release of odors, lack of consistent moisture may lead to incomplete decomposition in those parts of the windrow that are low in moisture. Assuring adequate moisture (greater than 40 percent) will go along way to ensuring even and complete decomposition of the windrow.

4.1.5 Avoid over-watering windrows:

Over-watering windrows can lead to a number of odor releases. Exceeding the recommended moisture content (typically no more than 60 percent) may inhibit air movement, leading to anaerobic conditions. Over-watering can also release free liquids which could pool at the base of the windrow, further inhibiting natural air flow and possibly creating puddles which can quickly become anoxic or anaerobic and lead to odors.

4.1.6 Make smaller windrows to increase passive aeration:

A smaller windrow profile will enhance natural convection and improve the distribution of oxygen in the pile, reducing the formation and persistence of anaerobic by-products. However, a smaller windrow also increases the surface areas for odors to escape from. This is particularly true for terpenes, so it may not be an appropriate mitigation for all feedstocks.

4.1.7 Diligently monitor and manage the composting process:

This could include monitoring temperatures, monitoring moisture, monitoring pH, and checking porosity. All of these refer to increasing the management intensity of the composting process. Monitoring temperature will help verify that the process is functioning and that adequate moisture is available. Measuring O_2/CO_2 content to determine oxygen levels will verify that air is getting to the interior of the pile and porosity is adequate. There are a number of readily available tools to measure either oxygen content or carbon dioxide production in a windrow. In general oxygen content above 5 percent (though higher is better) would be an indication of adequate porosity, leading to adequate aerobic conditions within a windrow. Checking pH may help identify an extreme of either acid or basic conditions, both of which can lead to odor release, though of different chemicals and for different reasons. Acidic conditions (below a pH of 5) may indicate formation of organic acids (see *Literature Review*). Basic conditions (above a pH of 8) may lead to excess volatilization of nitrogen and ammonia release (see *Literature Review*). There is a simple test to measure porosity and bulk density which may indicate a need to add bulking agent.

4.1.8 Increase porosity and bulk density:

Increasing porosity will increase natural airflow into the pile and will help maintain aerobic conditions. Adding a bulking agent may correct an imbalance of carbon to nitrogen ratio, and increase the porosity, as well as slowing the process down.

4.1.9 Consider blanketing the windrow with a six-inch to one-foot layer of bulking agent, high carbon amendments, or finished compost, (water lightly to reduce odor releases):

Research (Büyüksönmez, 2006) has shown that providing a “pseudo-biofilter” or a blanketing layer of finished compost over composting materials reduces the odorants being emitted from the composting materials. The same effect can be achieved by blanketing incoming materials with finished compost or other organic materials. Some facilities have used woody “overs” the oversize woody pieces screened out of finished compost to provide this same blanketing effect. Watering the “blanket” materials allows more odorants to be absorbed onto the woody particle. In addition, if you use finished compost, you may also get a benefit of the added finished compost to the in-process compost when the blanket is turned into the mass.

4.1.10 Make piles on a one-foot bed of overs to increase airflow:

Many compost facilities screen their final compost to remove oversize particles. These “overs” can be used to form a very porous “bed” on which a windrow can be placed. By placing the windrow on the overs bed, you can increase natural airflow, at least initially.

4.1.11 Adopt forced aeration:

Providing air to composting materials with a fan is a more certain way of supplying oxygen and avoiding anaerobic conditions. With certain feedstocks and in certain environments, forced aeration can minimize odors and in addition the collected air can be treated to further reduce odors. Forced aeration is no guarantee that anaerobic conditions will not develop because air distribution is not always uniform.

4.1.12 Adopt a contained method of composting:

There are a variety of composting methods and commercially-available systems which are designed to contain the composting materials within an enclosure, vessel, container, or other container. Most of these involve forced aeration in addition to isolating the composting mass from the ambient environment allowing the collected gases to be treated. These systems are relatively expensive but may be appropriate in certain situations.

4.1.13 Treat process exhaust gases in a biofilter or other treatment system:

In an aerated system (or a passive system within a building) process gases can be captured and then delivered to an odor treatment device. In many cases composting facilities utilize biofilters (an organic filter media designed to adsorb and decompose odorous compounds). Other chemical/physical treatment options exist including chemical scrubbers and non-thermal plasma treatment.

5.0 SCREENING

5.1 Screening Volatizes Particles

The act of screening releases and exposes many volatile particles and exposes them to the open air, promoting volatilization (release) of many odorous compounds.

5.1.1 Reduce screening activity during stagnant air conditions:

Stagnant air conditions, typical during temperature inversions, provide the least amount of odor dispersion and can lead to odor complaints, primarily because the air is moving very little or not at all and odors may concentrate and drift offsite if receptors are near. Although stagnant air conditions typically occur in the early morning or in the evening, inversions can occur anytime under the right conditions. If possible, reducing or eliminating screening or other materials handling activities during these conditions will reduce odor transport.

5.1.2 Reduce screening activity when wind is in direction of nearby receptors:

As discussed above, if possible, screening or other material handling activities should be scheduled when the wind is in a favorable dispersion direction (away from the nearest receptors).

5.1.3 Mist water or neutralizer at dust generation points:

Anywhere that dust is generated, odor is also likely generated. Most, if not all odorous chemicals released during composting are somewhat water-soluble. Misting (either with water or a water/odor neutralizer compound mix) can entrain at least some of the odorants as they fall to the ground.

6.0 OVERALL SITE

6.1 Water Allowed to Pond

Any water allowed to pond on a composting site carries organic compounds, nutrients and sediments that decompose in the water leading to odors.

6.1.1 Inspect piles after major rain events:

Inspecting the site regularly and especially after rain events can help identify areas where water may have ponded, leading to odor pockets. Severe rain events can also saturate materials leading to odor issues related to too much (>60 percent) moisture, which can lead to anaerobic conditions. Free liquid draining from windrows may be an indication of too much moisture.

6.1.2 Grade the site to eliminate puddles, depressions and wheel ruts where water collects:

Grading or re-grading the site will reduce the potential for ponding water.

6.1.3 Absorb ponded water with wood chips/other absorbent, fill pothole with soil/pad material:

This practice will help eliminate odors from ponded water.

6.2 Uncomposted Material in Aisles between Piles

Actively decomposing material in the aisles, especially fresh material, represent potential sources of odorants that readily escape into the air, they increase the surface area of passive emissions of odorous compounds. They can also become easily saturated during a rain event, further exacerbating this process.

6.2.1 Clean aisles of spilled material. (Particularly at the end of each day):

As discussed above, actively composting material in the aisles and at the end of rows increases the surface area of the overall site, increasing the area of emissions. Cleaning the aisles and ends of windrows by scraping can reduce this phenomenon.

6.2.2 Mechanically sweep paved areas at the end of each shift:

As discussed above, material in the aisles, especially fresh materials may increase the overall area emitting odorous chemicals.

6.2.3 Apply water and/or neutralizer to reduce dust during dry conditions:

Any dust leaving the composting site has the potential to also transport odors. Keeping aisles misted or watered can reduce dust transport.

7.0 CURING PILES

7.1 Excessive Decomposition in the Curing Pile

Curing is simply an additional phase of composting in which organic compounds continue to decompose, though at lower rates than in active composting. Anaerobic conditions may develop if materials are moved to a curing pile prematurely or if curing pile size or density prevents oxygen from diffusing.

7.1.1 Decrease curing pile size (height):

Very large curing piles (over 8 feet) may turn sour and be unable to aerate properly inhibiting the final stages of decomposition, Decreasing the pile size will improve diffusion of oxygen into the curing pile.

7.1.2 Increase processing time prior to moving to curing:

Excessive heat in a curing pile could also be an indication of incomplete decomposition. By increasing the time the material stays in the windrow, more complete decomposition can be ensured.

7.1.3 Review moisture content of in-process compost:

Un-even moisture in the composting mass may slow the composting process, moving this incompletely decomposed compost to a curing pile may reinvigorate biological activity and generate heat.

7.1.4 Screen after curing to maintain porosity:

Maintaining porosity in the curing pile will allow adequate natural aeration to complete the composting process.

7.1.5 Aerate curing piles:

If necessary, curing piles could be aerated with fans to provide needed oxygen.

8.0 Storm Water Basin

8.1 Excessive Nutrients in the Stormwater Basin

Drainage from rainfall coming in contact with organic materials may carry sediment and dissolved nutrients. In a storm water retention pond, these nutrients and sediments exert an oxygen demand (e.g., BOD) the majority of the BOD is associated with the sediments, which can be easily removed before the water enters the basin.

8.1.1 Review NPDES procedures to minimize storm water contact with organic materials:

Every facility should review its National Pollutant Discharge Elimination System Stormwater Management and Monitoring Plan to assure that all Best Management Practices are being properly implemented and are effectively reducing contact of storm water with organic materials.

8.1.2 Remove particles from water draining into stormwater retention basin:

A filter berm or other mechanism which slows the flow of stormwater runoff into a retention basin will help settle sediments or other organic materials picked up by storm water. Reducing the amount of these particles in the stormwater will reduce the total volume of nutrients in the stormwater, reducing the potential for overloading the pond with odor causing nutrients.

8.1.3 Filter stormwater through a filter berm or sock:

Some nutrients may be dissolved into stormwater and may be removed by using a filter berm or sock. It will also catch sediment, which is the most important.

8.1.4 Increase retention basin capacity:

If the stormwater retention pond is a constant source of odor due to dissolved nutrients, the basin may be undersized for the facility. Increasing the pond may help reduce the odors, or see the above mitigation measure for other measures to reduce nutrient inflow.

8.1.5 Clean retention basin during dry season:

If possible, the stormwater retention basin should be cleaned out prior to the next season's rainy period. This will prevent loss of retention capacity and also reduce the nutrient loading from the previous season's sediment.

8.1.6 Consider applying retained storm water to piles needing moisture:

Under certain circumstances, retained stormwater maybe used to add moisture to the compost piles. However, in most parts of California this is not very practical. In addition, care should be taken to ensure that retained stormwater is only added to piles prior to the pathogen reduction process being completed. Retained stormwater may contain pathogens.

8.1.7 Consider irrigating crops/pasture with retained storm water:

If nearby irrigated crops or pasture land is available, you may be able to utilize retained stormwater, thus preserving stormwater pond capacity and reducing the possibility of odors in the stormwater retention pond.

8.1.8 Provide aeration to stormwater retention basin:

Pond aerators have been used effectively in some compost facility stormwater retention basins to provide oxygen to the water in the pond and to strip some entrained chemicals.

Table 12: Summary of mitigation strategy menu

#	Source	#	Possible Cause	#	Management Approach
1	Feedstock receiving	1.1	Materials arriving with odors Amendment offsite prior to arrival	1.1.1	Mix materials upon receipt (increase material porosity).
				1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
				1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries.
				1.1.4	Make smaller piles.
				1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
				1.1.6	Enclose the receiving floor.
				1.1.7	Aerate receiving floor.
				1.1.8	Add lime or wood ash to piles to adjust pH.
				1.1.9	Reject odorous loads if possible.
				1.1.10	Eliminate troublesome feedstocks.
				1.1.11	Incorporate wet or odorous loads directly into actively composting windrows.
		1.2	Material sitting too long prior to being processed or mixed	1.2.1	Expedite material processing.
				1.2.2	Increase operating shifts.
				1.2.3	Reduce incoming throughput.
				1.2.4	Identify alternative outlets for incoming materials.
				1.2.5	First in, first out processing.
				1.2.6	Reduce size of material stockpiles.
				1.2.7	Increase collection frequency.
				1.2.8	Increase grinding/processing capacity (contract grinder/screener).
				1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
2	Grinding	2.1	Grinding volatilizes particles	2.1.1	Add light misting of water or odor neutralizer to grinder at discharge points.
				2.1.2	Consider scheduling grinding to coincide with favorable atmospheric dispersion conditions.
				2.1.3	Consider grinding green materials with woodier materials.
				2.1.4	Consider providing redundant equipment to assure on-time processing of materials.
				2.1.5	Identify alternative processing facilities for unexpected deliveries or equipment failures.

#	Source	#	Possible Cause	#	Management Approach
3	Mixing and Material Handling	3.1	Mixing volatilizes particles	3.1.1	Create windrows/piles that are sufficiently blended.
				3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
				3.1.3	Create piles with good porosity
				3.1.4	Mixing areas/activities should be located as far as possible from sensitive receptors
				3.1.5	Reduce mixing/materials handling activity during stagnant air conditions
				3.1.6	Reduce mixing/materials handling activity when wind is in direction of receptors
				3.1.8	Mist water or odor neutralizer at dust generation points
4	Composting	4.1	Less than ideal conditions	4.1.1	Reduce turning and/or material handling activity during stagnant air conditions
				4.1.2	Reduce turning/material handling activity when wind is in direction of nearby receptors
				4.1.3	Turn regularly to re-invigorate the composting process
				4.1.4	Maintain sufficient moisture in windrows
				4.1.5	Avoid over-watering windrows
				4.1.6	Make smaller windrows to increase passive aeration
				4.1.7	Diligently monitor and manage the composting process
				4.1.8	Increase porosity and bulk density
				4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost (water lightly to reduce odor releases)
				4.1.10	Make piles on a one-foot bed of overs to increase airflow
				4.1.11	Adopt forced aeration
				4.1.12	Adopt a contained method of composting
				4.1.13	Treat exhaust gases in a biofilter or other treatment system
				5.1.2	Reduce screening activity when wind is in direction of nearby receptors
				5.1.3	Mist water or neutralizer at dust generation points
5	Screening	5.1	Screening volatilize particles	5.1.1	Reduce screening activity during stagnant air conditions
				5.1.2	Reduce screening activity when wind is in direction of nearby receptors
				5.1.3	Mist water or neutralizer at dust generation points

#	Source	#	Possible Cause	#	Management Approach
6	Site	6.1	Water allowed to pond	6.1.1	Clean aisles of spilled material. (Particularly at the end of each day)
				6.1.2	Grade the site to eliminate puddles, depressions, and wheel ruts where water collects
				6.1.3	Absorb ponded water with wood chips/other absorbent, fill pothole with soil/pad material
		6.2	Uncomposted material on aisles	6.2.1	Clean aisles of spilled material. (Particularly at the end of each day)
				6.2.2	Mechanically sweep paved areas at the end of each shift
				6.2.3	Apply water and/or neutralizer to reduce dust during dry conditions
7	Curing Piles	7.1	Excessive temperature	7.1.1	Decrease curing pile size (height)
				7.1.2	Increase processing time prior to moving to curing
				7.1.3	Review moisture content of in-process compost
				7.1.4	Screen after curing to maintain porosity
				7.1.5	Aerate curing piles
8	Storm water retention basin	8.1	Excessive nutrients In storm Water runoff	8.1.1	Review NPDES procedures to minimize storm water contact with organic materials
				8.1.2	Remove particles from water draining into stormwater retention basin
				8.1.3	Filter stormwater through a filter berm or sock
				8.1.4	Increase retention basin capacity
				8.1.5	Clean retention pond during dry season
				8.1.6	Consider applying retained storm water to piles needing moisture
				8.1.7	Consider irrigating crops/pasture with retained storm water
				8.1.8	Provide aeration to stormwater retention basin

Table 13: Interactive odor mitigation alternative matrix

	Representative		Feedstocks					Operations							
Vial #	Odor Descriptors	Chemical	Green material	Food scraps	Manure	Biosolids	MSW	1- Receiving	2- Grinding	3- Mixing	4- Composting	5- Screening	6- Site	7- Curing Pile	8- Stormwater
1	Pungent Medicinal Irritating Urine Ammonia	Ammonia	√ **1**	√	√√ **(2)**	√	√√ **(3)**	**1**		**9**	**16**				
2	Fishy Putrid Decaying	Amines Mix Methyl Amine Dimethyl amine Trimethyl amine	√ **(1)**	√	√√		√√ **(3)**	**2**		**10**	**17**				
6	Decaying flesh Putrid Nauseating Dead Animal	Putracine Cadaverine		√ **(4)**			√√ **(5)**	**3**		**11**	**18**				
3	Piney Woody Sharp	Terpenes Eucalyptol Pinene	√√					**4**	**8**	**12**		**22**	**23**		

Vial #	Representative		Feedstocks					Operations							
	Odor Descriptors	Chemical	Green material	Food scraps	Manure	Biosolids	MSW	1- Receiving	2- Grinding	3- Mixing	4- Composting	5- Screening	6- Site	7- Curing Pile	8- Stormwater
	Lemony Grassy	Limonene													
4	Rotten Cabbage Skunky Decaying vegetation	Mercaptans Methyl mercaptan Ethyl mercaptan		√	√√ **(6)**	√	√ **(7)**	5		13	19		24	27	30
5	Sulfur Rotton Egg Garlicky	Reduced Sulfides Dimethyl disulfide Hydrogen sulfide dimethyl disulfide		√	√√	√√	√ **(7)**	6		14	20		25	28	31
7	Rancid Vinegary Putrid Sour Milk	Organic acids Butyric acid Acetic acid Valeric acid	√ **(1)**	√√	√			7		15	21		**26**	29	32

Vial #	Representative		Feedstocks					Operations							
	Odor Descriptors	Chemical	Green material	Food scraps	Manure	Biosolids	MSW	1- Receiving	2- Grinding	3- Mixing	4- Composting	5- Screening	6- Site	7- Curing Pile	8- Stormwater
	Decayed Garbagey														

To go to a list of specific mitigation alternatives, hold “control” down and click on the number.

5. 1. If grass is abundant
6. 2. Especially in poultry manure
7. 3. If fish or fish processing waste is present
8. 4. If meat or protein is present

1. Mitigation alternatives for ammonia at the receiving

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
1.1.9	Reject odorous loads if possible.
1.1.11	Incorporate wet or odorous loads directly into actively composting windrows
1.2.1	xpedited material processing
1.2.7*	Increase collection frequency*
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

*if grassy

2. Mitigation alternatives for amines at the receiving

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.4	Make smaller piles
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
1.1.7	Aerate receiving floor.
1.1.9	Reject odorous loads if possible.
1.1.11	Incorporate wet or odorous loads directly into actively composting windrows
1.2.1	Expedite material processing
1.2.7	Increase collection frequency
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

*if grassy

3. Mitigation alternatives for putracine and cadaverine at the receiving

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.4	Make smaller piles
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
1.1.7	Aerate receiving floor.
1.1.9	Reject odorous loads if possible.
1.1.11	Incorporate wet or odorous loads directly into actively composting windrows
1.2.1	Expedite material processing
1.2.7	Increase collection frequency
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

4. Mitigation alternatives for terpenes at the receiving area

1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases).
1.2.1	Expedite material processing
1.2.8	Increase grinding/processing capacity (contract grinder/screener)
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

5. Mitigation alternatives for mercaptans at the receiving area

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.4	Make smaller piles
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases).
1.1.8	Add lime or wood ash to piles to adjust pH
1.2.1	Expedite material processing
1.2.6	Reduce size of material stockpiles
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

6. Mitigation alternatives for ammonia at the receiving area

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.4	Make smaller piles
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
1.1.8	Add lime or wood ash to piles to adjust pH
1.2.1	Expedite material processing
1.2.6	Reduce size of material stockpiles
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

7. Mitigation alternatives for ammonia at the receiving area

1.1.1	Mix materials upon receipt (increase material porosity)
1.1.2 *	Stockpile bulking agent or high carbon amendments as receiving basin.
1.1.3 *	Stockpile bulking agents or high carbon amendments for unexpected deliveries
1.1.4	Make smaller piles
1.1.5	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases).
1.1.9	Reject odorous loads if possible.
1.1.11	Incorporate wet or odorous loads directly into actively composting windrows
1.2.1	pedite material processing
1.2.6	Reduce size of material stockpiles
1.2.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

*if food waste

8. Mitigation alternatives for terpenes at grinding

2.1.1	Add light misting of water or odor neutralizer to grinder at discharge points
2.1.3	Consider grinding green materials with woodier materials.

9. Mitigation alternatives for ammonia at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.8	Mist water or odor neutralizer at dust generation points

10. Mitigation alternatives for amines at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.3	Create piles with good porosity

11. Mitigation alternatives for putracine and cadaverine at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.3	Create piles with good porosity

12. Mitigation alternatives for terpenes at mixing

3.1.1	Create windrows/piles that are sufficiently blended.

13. Mitigation alternatives for mercaptans at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.3	Create piles with good porosity

14. Mitigation alternatives for reduced sulfur compounds at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.3	Create piles with good porosity

15. Mitigation alternatives for organic acids at mixing

3.1.1	Create windrows/piles that are sufficiently blended.
3.1.2	Combine materials to achieve a high C:N ratio (greater than 30 to 1)
3.1.3	Create piles with good porosity

16. Mitigation alternatives for ammonia at composting

4.1.4	Maintain sufficient moisture in windrows
4.1.7*	Diligently monitor and manage the composting process
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

*with particular attention to pH

17. Mitigation alternatives for amines at composting

4.1.3	Turn regularly to re-invigorate the composting process
4.1.5	Avoid over-watering windrows
4.1.6	Make smaller windrows to increase passive aeration
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

18. Mitigation alternatives for putrascine and cadaverine at composting

4.1.3	Turn regularly to re-invigorate the composting process
4.1.5	Avoid over-watering windrows
4.1.6	Make smaller windrows to increase passive aeration
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)

19. Mitigation alternatives for mercaptans at composting

4.1.3	Turn regularly to re-invigorate the composting process
4.1.5	Avoid over-watering windrows
4.1.6	Make smaller windrows to increase passive aeration
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
4.1.11	Adopt forced aeration

20. Mitigation alternatives for reduced sulfur compounds at composting

4.1.3	Turn regularly to re-invigorate the composting process
4.1.5	Avoid over-watering windrows
4.1.6	Make smaller windrows to increase passive aeration
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
4.1.11	Adopt forced aeration

21. Mitigation alternatives for organic acids at composting

4.1.3	Turn regularly to re-invigorate the composting process
4.1.5	Avoid over-watering windrows
4.1.6	Make smaller windrows to increase passive aeration
4.1.9	Consider blanketing odiferous materials with a six inch to one-foot layer of bulking agent, high carbon amendments, or finished compost. (water lightly to reduce odor releases)
4.1.11	Adopt forced aeration

22. Mitigation alternatives for terpenes at screening

Nothing in particular

23. Mitigation alternatives for terpenes at the site

6.1.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.2	Mechanically sweep paved areas at the end of each shift

24. Mitigation alternatives for mercaptans at the site

6.1.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.2	Mechanically sweep paved areas at the end of each shift
6.2.3	Apply water and/or neutralizer to reduce dust during dry conditions

25. Mitigation alternatives for reduced sulfur compounds at the site

6.1.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.1	Clean aisles of spilled material. (Particularly at the end of each day)
6.2.2	Mechanically sweep paved areas at the end of each shift
6.2.3	Apply water and/or neutralizer to reduce dust during dry conditions

26. Mitigation alternatives for organic acids at the site

Nothing in particular

27. Mitigation alternatives for mercaptans at curing

7.1.1	Decrease curing pile size (height)
7.1.2	Increase processing time prior to moving to curing
7.1.3	Review moisture content of in-process compost
7.1.4	Screen after curing to maintain porosity
7.1.5	Aerate curing piles

28. Mitigation alternatives for reduced sulfur compounds at curing

7.1.1	Decrease curing pile size (height)
7.1.2	Increase processing time prior to moving to curing
7.1.3	Review moisture content of in-process compost
7.1.4	Screen after curing to maintain porosity
7.1.5	Aerate curing piles

29. Mitigation alternatives for organic acids at curing

7.1.1	Decrease curing pile size (height)
7.1.2	Increase processing time prior to moving to curing
7.1.3	Review moisture content of in-process compost
7.1.4	Screen after curing to maintain porosity
7.1.5	Aerate curing piles

30. Mitigation alternatives for mercaptans in runoff

8.1.1	Review NPDES procedures to minimize storm water contact with organic materials
8.1.2	Remove particles from water draining into stormwater retention basin
8.1.3	Filter stormwater through a filter berm or sock

31. Mitigation alternatives for reduced sulfur compounds in runoff

8.1.1	Review NPDES procedures to minimize storm water contact with organic materials
8.1.2	Remove particles from water draining into stormwater retention basin
8.1.3	Filter stormwater through a filter berm or sock

32. Mitigation alternatives for organic acids in runoff

8.1.1	Review NPDES procedures to minimize storm water contact with organic materials
8.1.2	Remove particles from water draining into stormwater retention basin
8.1.3	Filter stormwater through a filter berm or sock

Local Government Guide

Executive Summary

Composting facilities face unique and persistent challenges in developing and maintaining a sustainable site. The C-CORP Project has developed a number of tools to assist operators and LEAs in understanding and mitigating odors from composting facilities. The Local Government Guide is a concise summary of background principles and planning considerations designed to be used by city and county planning staff and local government decision makers in the early stages of planning and permitting a compost facility. The Local Government Guide discusses critical planning concepts rather than providing a step-by-step process guide. Topics discussed include zoning and master planning, community involvement, and coordinating compost facility planning with current and Planned AB 939 plans ad franchise agreements.

A Concise Guide to Planning a Composting Facility

A Guide for Local Government

Developing almost any major facility is a challenge in California, and a composting facility is no different. Composting facilities also provide unique challenges in maintaining a sustainable site. Urban encroachment is a major factor in the closure or relocation of many major composting facilities. The following guide provides some background principles in planning a composting facility in California, with a particular focus on planning considerations and mitigations. The CIWMB also provides additional guidance on its web site for specific CEQA-related environmental considerations (http://www.ciwmb.ca.gov/leacentral/ceqa/compost.htm) as well as regulatory considerations (http://www.ciwmb.ca.gov/PermitToolbox/GeneralInfo/ProcessFlow.htm).

Zoning and Master Plans

AB 939 (Sher 1989) fundamentally changed the way solid waste and recyclables (including those materials collected for composting, like green materials) are planned for and managed in California. Each city and county is responsible for planning for and diverting 50 percent of its solid waste stream from landfill disposal. Each County now maintains a Countywide Integrated Waste Management Plan (CoIWMP). The CoIWMP contains a description of all of the programs a given jurisdiction (or group of jurisdictions) plans to use to achieve its AB 39 mandated landfill diversion. The county typically prepares this document.

While the CoIWMP describes the types of programs a jurisdiction will use, it typically does not specifically describe where these facilities will be located. A jurisdiction needs to plan for this needed infrastructure just as it planned for its landfill or wastewater treatment plant. Composting facilities need to be located in appropriate zones. Typically these are either agricultural or industrial zones, though some light industrial or heavy commercial zones may also be appropriate.

Community master planning should take into account the need for recycling infrastructure like composting. Correct zoning and planning (and enforcement of these designations), can lead to the sustainability of a local composting facility, assuring cost-effective local processing.

One option may be to locate composting facilities at or near existing solid waste facilities (like landfills) or wastewater treatment plants. A landfill can be an ideal location for a composting facility as it is likely located in an appropriately zoned area and already manages many of the impacts that composting facilities can have (truck traffic, noise, occasional odors, etc.). Landfills may also have existing buffer areas (for future development) that may be available (if temporarily) for use by the composting facility. Similarly, wastewater treatment plants may have available buffer or future growth areas that could be used by a composting facility. Several examples of regional composting facilities located on landfills are listed in Table 14.

Table 14: Landfills with Composting Facilities in California

Facility	Location
Merced County's Highway 59 landfill and composting facility	Merced
Monterey Regional Waste Management District (two composting facilities located on one regional landfill)	Marina
Newby Island landfill and composting facility	San Jose (Milpitas)
Sonoma County Central Landfill	Petaluma
B&J sanitary Landfill/Jepson Prairie Organics	Dixon
West Contra Costa Sanitary Landfill and Composting Facility	Richmond
City of San Diego's Miramar landfill and composting facility	San Diego
Lake View Terrace (Lopez Canyon Landfill)	Los Angeles

Locating a composting facility at a landfill will be successful only if the original zoning that led to the landfill being sited in the area is preserved and protected from residential or other non-compatible uses. Urban encroachment also can and does affect landfills.

Community involvement in initial project planning and CEQA

Early involvement by major stakeholders (i.e., neighbors, local health officials, city and county planners, and others) is key to the acceptance of a major composting facility. Planning meetings should be held as far as practical prior to the establishment of the composting facility taking into account potentially affected parties, zoning, existing and planned land use, and solid waste diversion plans. Recent studies by the Water Environment Federation suggest that early involvement in the planning process by all stakeholders, but in particular the public can both facilitate the development process, but also help the facility down the road if odors or other "impacts" occur. The key is a move away from "one-way, public relations based communications to two-way public relationship building initiatives" (Goldstein 2006).

The level of community involvement is commensurate with the size and complexity of the project. A small on-farm or on-site composting operation may require little community involvement, whereas a major regional food scraps and green material composting facility may require significant community involvement and planning. The tools and techniques that a facility or a community uses can vary but might include regular newsletters, videos, public service announcements, websites, hotline numbers, etc. All of these tools support regular public meetings and the work of a "Local Advisory Committee". A local advisory committee might be comprised of various respected and trusted members of the community who meet regularly to discuss the project.

An important and sometimes overlooked aspect of the outreach process is effectively communicating the need for the facility (to reduce dependence on landfills and increase recycling) and the benefits of using compost in the community. The following link provides information on a national effort to understand public perceptions, risk perceptions, communications and stakeholder involvement. Although this project focuses on biosolids, its tools and conclusions are widely applicable to composting facilities, regardless of feedstock (www.nebiosolids.org/pdf/ 1073947971RiskPercp-InvolveJan04Final.ppt).

An important and not widely understood aspect of odor perception is odor bias. Properly conducted community outreach can go along way towards minimizing or driving odor perceptions and bias.

How Can Odors be Minimized?

Every compost facility can expect to have some issues with odor. Each commercial compost facility is required to prepare and maintain a site-specific Odor Impact Minimization Plan ((Title 14 California Code of Regulations, Chapter 3.1 §17863.4) (OIMP) that is enforced by the Local Enforcement Agency. In general, the theory behind the OIMP process is that if a facility generates odor complaints, it must implement procedures contained within its OIMP to mitigate those odors. A comprehensive Odor Mitigation Strategy Menu (OMSM) has been developed by the CIWMB (http://www.ciwmb.ca.gov/leacentral/organics/ccorp/default.htm).

The mitigations contained in the OMSM are generally management level actions an operator can take to reduce or mitigate odors. Once the "management" techniques are exhausted, a facility may have to consider increasing process control through technology. Aerated Static Piles can offer increased compost process control and if conducted in a negatively aerated system (drawing rather than blowing air), the airflow can be captured and consolidated for further controls. Once consolidated, the odors from a composting operation can be run through a variety of filters. An operator should be required to submit their OIMP early in the planning process.

A Note on Odor Bias:

Individuals differ greatly in their perception odors. However, the differences in people's reactions to odors go well beyond their olfactory perceptions. People also interpret and respond to odors according to their historic associations, attitudes and expectations. In an article in BioCycle magazine (Dalton, 2003), Pamela Dalton, psychologist with the Monell Chemical Senses Center, writes the following. "Research has shown that people's reaction to odor and their beliefs about the effects from odor are influenced by a diverse set of factors including personality traits, personal experience and information or social cues from the community and media. These factors can increase, or in some cases decrease, a person's sensitivity and awareness of environmental odors." In short, what an individual feels and believes about an odor influences his/her response.

Dalton's research, demonstrates the influence of two psychological factors on odor perception - expectations and social cues. In one experiment, three different groups of volunteers were exposed to 20 ppm of n-butyl alcohol, which is not pleasant smelling but not an irritant at that concentration. Beforehand, one group was given a positive bias by telling them that the chemical was a natural plant extract. The second group was told that the chemical was a standard laboratory odorant (neural bias). The third group was told that it was an industrial degreasing chemical (negative bias). All three groups were exposed to the same concentration of the same chemical. Nevertheless, the group given the negative bias reported significantly greater symptoms of throat, eye and nose irritation than the neutral bias group. The positive bias group reported significantly fewer symptoms.

In another experiment in Dalton's lab, three groups of volunteers were asked to smell an unidentified odorant (acetone was used). Planted within each group was a "confederated subject" -- a paid actor who was instructed to orally respond either positively (e.g. increases alertness), negatively (e.g. irritates eyes) or in a neutral manner. The volunteers were asked to rate the odor intensity every minute over the 20-minute exposure duration. The odor intensity ratings for the groups hearing the positive and neutral biases generally decreased during the experiment. The decrease was due to adaptation, which typically occurs during continued exposure to a constant odor. However, the odor intensity ratings of the negatively biased group increased over time. The negative comments of the confederate subject influenced the other volunteers that the odor was getting more intense. In addition, the negatively biased group reported significantly more nausea, drowsiness and eye and nose irritations.

Negative expectations are likely to prompt a negative response. When neighbors are already conditions to expect malodors from a composting facility they are more likely to notice them. Furthermore, they will perceive more serious consequences when they believe the odors present risks. They may even feel ill in the absence of harmful chemicals. Whether they know it or not, an activist neighbor protesting a facility is conditioning other neighbors to perceive the situation in a negative manner.

What types of technologies and designs are available for composting?

The type of composting system may have an impact on its potential to create nuisances in a community. In general, the more likely a facility is to have impacts, the more “process control” should be a major consideration. However, technologies with increased in process control are generally more expensive than systems with less process control. The overwhelming majority of commercial composting is done outside in a windrow process (elongated pile turned with simple or specialized equipment). However windrows can be more or less intensively managed, which may have an effect on odor production. Certain siting limitations or circumstances may require additional process control. In general, increases in process control require increases in operating and/or capital costs. There are myriad systems available that provide additional process control; these are listed in “Modern Composting Technologies” (Chiumenti, 2005). This book provides the most up-to-date information about composting systems and equipment.

In general composting systems can be divided into 5 major categories, though many systems are actually hybrids of one or more systems. A general description of these systems is contained in Table 15. In general, compost process control increases from the top to the bottom of the table. The type of composting system should be decided upon as early in the process as possible.

Table 15: General description of composting technologies

General Category	Description
Passively aerated - static	Windrow or “static pile” – not regularly turned
Passively aerated – turned/agitated	Turned windrow
Forced aerated – static	Aerated static pile – aeration can be either positive or negative, but not regularly turned
Forced aerated and turned/agitated	Turned aerated static pile – aeration can be either positive or negative, regularly turned or agitated.
Contained or “in-vessel”	Varies by system

What should you consider for mitigating noise?

There are several potential sources of noise at a composting facility. The loudest source of noise is typically the grinder, though not all facilities will have grinders. In addition, the back-up alarms of front-end loaders is also very distinctive. Other material handling and truck idling can also contribute to noise. Some, but not all communities have specific noise ordinances that may set specific decibel levels for the area. These may or may not be accompanied by specific "quiet" hours. The layout of the facility can mitigate noise somewhat. Windrows of compost tend to absorb noise somewhat. Other noise mitigations include:

- Maintaining all equipment in accordance with manufacturer's recommendations.
- Maintaining mufflers in working condition on all equipment.
- Adhering to hours of operation which coincide with local noise ordinances.

Site layout can also impact off-site noise impacts. Locating processing equipment away from site boundaries (if feasible) and using the natural sound attenuation of large piles of organic materials (piles of chipped wood or compost piles should be taken advantage of if possible.

Should you consider future growth patterns in your community?

When considering a composting facility's location, significant attention should be paid to the future or planned growth in the surrounding area. Is the composting facility located near similar uses? Is residential growth heading directly towards the proposed facility? Is the zoning amenable to an industrial facility with potential off-site impacts? What is a reasonable buffer zone?

For general situations, it is impractical to establish a buffer distance that will eliminate all odor complaints. Odors have been known to travel a few miles in large enough concentrations to elicit complaints. For specific facilities in specific locations, odor modeling can be used to predict the number of impacts on neighbors. However, it must be emphasized that the nature, topography and management of the specific facility, plus the attitude and expectation of neighbors, determine the frequency and distance of odor complaints. Some composting facilities operate successfully within a few city blocks of residential neighborhoods. Some facilities in seemingly remote locations have been plagued by odor complaints from neighbors miles away. In summary, although setting a minimum buffer distance provides some degree of protection from odor impacts, it is very difficult to establish a good general standard.

How can you make sure that planners and local enforcement agency interact?

A key to success of the early planning stages of a composting facility is interaction between Planning staff and the Local Enforcement Agency (LEA). Any commercial composting facility will be required to obtain a solid waste facility permit. The LEA will be the primary entity enforcing the solid waste facility permit and is likely the agency with the most experience with composting. The Planning Department may not have much experience with the solid waste facility permit process. (http://www.ciwmb.ca.gov/PermitToolbox/GeneralInfo/ProcessFlow.htm). The LEA (typically a County employee) should be brought into the planning process as early as possible.

What plans should an operator have for responding to community concerns?

Operators should make presentations to local community development organizations (if in unincorporated areas) and planning commission or city council in incorporated areas. As described above, the more complex a project, the more important are upfront planning, communication and stakeholder involvement. Once a facility is operating, the facility should have a written plan to facilitate community communication, and to handle incoming complaints or concerns. Positive events a facility can have include open house events at the facility, and/or donations of compost to local projects (little league fields, community improvement projects, etc.). A written "script" for staff to use to handle and log complaints is often included in a facility's Odor Impact Minimization Plan.

How do your current and planned AB 939 programs mesh with the project?

As mentioned above, every city and county is responsible for planning for its AB 939-mandated landfill diversion. A document called a Source Reduction and Recycling Element (SRRE) describes the programs that the community has chosen to meet these requirements. Every jurisdiction is required to demonstrate 15 years of landfill capacity. The landfill(s) your community will rely on are described in the Countywide Siting Element. All of the non-landfill diversion programs are described in the aptly named Non-Disposal Facility Element (NDFE). A new composting facility would need to be "identified" in the NDFE prior to its being permitted by the CIWMB. Identifying the proposed facility in the NDFE and determining whether or not it is compatible with the existing and planned diversion programs in a given community is a key element to the early planning stages of a composting facility.

Composting facilities can have a major impact on the success of a given jurisdiction's ability to comply with AB 939. In fact it has been said that a jurisdiction can not realistically achieve 50 percent landfill diversion without diverting at least some of the organic waste stream (like green material and food scraps).

How do your current and planned franchise agreements mesh with the project?

In most jurisdictions, collection of solid waste and recyclables (including green material) is controlled via a "franchise agreement". A franchise agreement typically is a contract between a given jurisdiction and a collection company to provide the collection of residential or commercial materials. Some communities operate under "exclusive" franchise agreements, which give the exclusive right to collect a given material (say curbside recyclables) to a particular company. Other jurisdictions have "open" or non-exclusive" franchise agreements. A franchise may or may not specify how and where a material is to be handled. In the case of green material collection, the franchise agreement may or may not specify a specific facility (like a compost facility). In other cases, it may be left to the collector to provide the final location of the material. However, some facilities may handle material that is not covered in a jurisdiction's franchise agreement and they may not rely on the franchise hauler to provide it. These facilities are sometimes referred to as "merchant" facilities.

City or County staff that is familiar with the jurisdiction's franchise arrangements should be consulted during the initial planning process.

References and Additional Resources

Chiumenti, A., R. Chiumenti, L.F. Diaz, G.C. Savage, L.L. Eggerth and N. Goldstein. 2005. Modern Composting Technologies, The JG Press, Inc. Emmaus, PA.

Dalton, P. (2003) How people sense, perceive and react to odors. *BioCycle*, Vol. 44, n 11, pp. 26.

Goldstein, N. (2006) Neighbor-Friendly Odor Management *BioCycle*,Vol. 47, No. 3 pp. 43.

Comprehensive Compost Odor Response Project Documents:

http://www.ciwmb.ca.gov/leacentral/organics/ccorp/default.htm

References

Accortt, J. R. Krause, and R. Rynk, 2001. Air handling holds key to odor management. *BioCycle*: 42(10): 54-55

Answers.com., 2005a. Indoles. http://www.answers.com/Indoles.

Answers.com., 2005b. Aldehydes. http://www.answers.com/Aldehydes.

BioCyle, 2004. Odor Management at Composting Facilities, J.G. Press, Emmaus, PA.

Brant, R.C. and H.A. Elliott, 2004. Odor Management in Agriculture and Food Processing in Pennsylvania, Pennsylvania State University, University Park, PA.

Buckner, S.C., 2002a. Effects of Turning Frequency and Mixture Composition on Process Conditions and Odor Concentrations during Grass Composting, In Proceeding of the 2002 International Symposium, Columbus Ohio, May 2002.

Buckner, S.C., 2002b. Controlling Odors during grass composting, *BioCycle*, 43(9) p. 42-47.

Buyuksonmez, F and Yucel, A. Odor Mitigation Alternatives. 14th Annual U.S. Composting Council Conference. Albuquerque, TX. January 2006.

Cain, W.S., 2006. Perception and Reality of Odor. Presentation at the U.S. Composting Council Annual Conference, Albuquerque, NM, January 2006.

California Integrated Waste Management Board, 2005. Odor Impact Minimization Plan, Title 14 California Code of Regulations, Chapter 3.1 §17863.4 http://www.ciwmb.ca.gov/Regulations/Title14/ch31.htm#article3

Campbell, A.G., R.L. Folk and R.R. Tripepi, 1997. Wood ash as an amendment in municipal sewage sludge and yard waste composting processes. Compost Science and Utthzation, 5(1):62-73.

Chastain, J.P. and F.J. Wolak, 2000. Application of a Gaussian Plume Model of Odor Dispersion to Select a Site for Livestock Facilities. Proceedings of the Odors and VOC Emissions 2000 Conference, sponsored by the Water Environment Federation, April 16-19, Cincinnati, OH.

Chiumenti, A., R. Chiumenti, L.F. Diaz, G.C. Savage, L.L. Eggerth and N. Goldstein, 2005. Modern Composting Technologies, The JG Press, Inc. Emmaus, PA.

Cotton, M., Integrated Waste Management Consulting, 2005. Personal communication

Dalton, P., 2003a. How People perceive Odors. Presentation at *BioCycle* West Coast Conference, Los Angeles, March 2003.

Dalton, P., 2003b. How people sense, perceive and react to odors. *BioCycle*, Vo. 44, n 11, pp. 26.

Das, K.C., 2000 Odor Related Issues in Commercial Composting, Workshop presented at the Y2K Composting in the Southeast Conference & Expo, October, 2000, Charlottesville, VA.

Day M. and K. Shaw, 2001. Biological, Chemical, and Physical Processes of Composting. Chapter in: Compost Utilization in Horticultural Cropping Systems. P.J. Stoffella and B.A. Kahn (eds.) CRC Press. 2001.

Defoer et al, 2002. Gas chromatography–mass spectrometry as a tool for estimating odour concentrations of biofilter effluents at aerobic composting and rendering plants. *Journal of Chromatography A*, 970: 259–273.

de Nevers, N., 2000. Air Pollution Control Engineering, The McGraw-Hill Companies, Inc. Boston. MA.

Derikx, P.J.L., Op den Camp, H.J.M. van der Drifts, C., Vogels, G.D., van Griensven, L.J.L.D., 1990. Odorous Sulfur Compounds Emited During production of Compost Used as a Substrate in Mushroom Cultivation. *Applied Mircrobiology*, Vol 56 (1).

Dravnieks, A. and H.J., O'Niel., 1979. Annoyance Potentials of Air Pollution Odors, *J. Am Ind. Hyg. Assoc.* 40 (February).

Dravnieks, A., 1979. Odors from stationary and mobile sources. National Academy of Science Publications, Washington, D.C.

E & A Consultants, 1993. Food Waste Collection and Composting Demonstration Project. Final Report for City of Seattle Solid Waste Utility, Bothell, WA.

Eitzer, B.D., 1995. Emissions of volatile organic chemicals from municipal solid waste composting facilities. *Environmental Science and Technology*, 29(4): 896-902.

Elwell, D.L., D.C. Borger, D.V. Blaho, J.K. Fahrni, H.M. Keener, and L.B. Willett, 2004. Changes in concentrations of malodorous compounds during controlled aeration composting. In Proceeding of the 2002 International Symposium, Columbus Ohio, May 2002.

Elwell, D.L., D.C. Borger, D.V. Blaho, J.K. Fahrni, H.M. Keener, and L.B. Willett, 2002a. Changes in concentrations of malodorous compounds from fresh and aged dairy manure during controlled aeration composting. *Compost Science and Utilization* 12(2) 102-107.

Elwell, D.L., J.H. Hong, and H.M. Keener, 2002b. Composting hog manure/sawdust mixtures using intermittent and continuous aeration: Ammonia emissions. *Compost Science and Utilization* 10(2): 142-149.

Epstien, E., 1997. *The Science of Composting*. Technomic Publishing Company, Penn.

Fraser and Lau, 2000. The Effects of Process control Strategies on composting Rate and Odor Emission, *Compost Science and Utilization* 8(4): 274-292.

Goldstein, N., 2006. Neighbor-friendly odor management, *BioCycle*, Vol. 47(3).

Goldstein, N., 2002. Getting to Know the Odor Compounds, *BioCycle*, Vol. 43(7).

Haug, R.T., 1993. *The Practical Handbook of Compost Engineering*. Lewis Publishers, CRC Press, Boca Raton, Florida.

Haug, R.T., 2004, Elements of Odor Management. In Odor Management at Composting Facilities, J. G. Press, Emmaus, PA.

Hentz, L.H. Jr., W.E. Toffey, and C.E. Schmidt, 1996. Understanding the synergy between composting and air emission, *BioCycle* 37, no. 3: 67-72, 74-75.

Hoitink, H.A.J., and H.M. Keener, eds., 1993. Science and Engineering of Composting, Ohio State University, Wooster.

Iacoboni, M.D., T.J. Leburn, and J. Lingston, 1980. Deep windrow composting of dewatered sewage sludge, pp. 88-108. In *Proc. Nat'l. Conf. Municipal & Inustrial Sludge Composting*, Philadelphia. PA.

Kayhanian and Tchonbanoglous, 1992. Computation of C/N ratios of various organic fractions. *BioCycle*, 33(5) 58-60.

Kephart, K. B., and R. E. Mikesell, 2000. Manure Odors Department of Dairy and Animal Science. Pennsylvania State University, State College, PA.

Kuter, G.A., 1990. Odor control—completing the composting process. International—process systems, Inc., 655, Winding Brook Dr., Glastonbury, CT.

Kuroda, K., T. Osada, M. Yonaga, A. Kanematu, T. Nitta, S. Mouri, and T. Kojima, 1996. Emissions of malodorous compounds and greenhouse gases from composting swine feces. *Bioresource Technology*, (56): 265-271.

Liu, D.H.F., B.G. Liptak, and P.A. Bouis, eds., 1997. Environmental Engineers' Handbook, Lews Publishers, New York, NY.

Lystad, H., J.P. Hammer, R. SØrhein, O. Molland, O. Bergersen, and P. Smits, 2002. Using lime to reduce odors from biowaste composting. *BioCycle*, 43(9) 38-41.

Martinson, S. Massachusetts Department of Environmental Protection,. 2003. Personal communication.

McGinley, M.A., and C.M. McGinley, 2005. Measuring Compost Odors for Decision Making. Presented at the U.S. Compost Council 2005 Annual Conference, San Antonio, TX.

McGinley, C.M., T.D. Mahin, and R.J. Pope, 2000. Elements of Successful Odor/Odour Laws. Presented at WEF Odor/VOC 2000 Specialty Conference, Cincinnati, Ohio.

Michel F.C., Jr., R.F. Rynk and H.A.J. Hoitink, eds, 2002. Proceeding of the 2002 International Symposium, Columbus Ohio, May 2002. JG Press, Emmaus, PA.

Michel, F.C., 2002. Effects of Turning and feedstocks on yard trimming composting. *BioCycle*, Vol. 43(9): 46.

Michel, F.C., 1999. Managing compost piles to maximize natural aeration. *BioCycle*, Vol. 40(3): 56-58.

Michel, F.C., L.J. Forney, A.J.F. Huang, S. Drew, M. Czuprenski, J.D. Lindeberg, and C.A. Reddy, 1996. Effects of Turning Frequency, Leaves to Grass Mix Ratio and Windrow vs. Pile Configuration on the Composting of Yard Trimmings. *Compost Science and Utilization* 4(1).

Miller, F.C., 1993. Minimizing Odor Generation. In Science and Engineering of Composting. Ohio State University, pp. 219.

Miner, J.R., 1995. An executive summary: A review of the literature on the nature and control of odors from pork production facilities. http://www.nppc.org/PROD/EnvironmentalSection/odorlitreview.html (verified 5/01/99).

Natural Resources Conservation Service (NRCS), 2006. Wind Rose Data: March 2006. http://www.wcc.nrcs.usda.gov/climate/windrose.html.

Myers, L., 2004. Odor Management Strategy Meets Neighbor Approval. *BioCycle*, Vol. 45(9):50-54.

Natural Resources Conservation Service (NRCS), 1999. Conservation practice standard – Herbaceous wind barriers. Code 422A. February 1999.

Noble et al, 2001. Atmospheric Pollutants and Trace Gases—Olfactory Response to Mushroom Composting Emissions as a Function of Chemical Concentration. Technical Report.

Oshins, C., 2006. Composting Process. In: On Farm Composting Handbook, 2nd Edition, NRAES. Ithica, NY. Unpublished draft.

Paul, J. Transform Compost Limited, 2006. Personnel communication.

Pelosi, R., 2003. Clearing the Air. *American City & County*. http://www.americancityandcounty.com/.

Richard, T., 2005. The Effect of Lignin on Biodegradability. Cornell Composting. http://compost.css.cornell.edu/calc/lignin.html.

Richard, T.L., B. Hamelers, A. Veeken, and T. Silvia, 2002. Moisture relationships in composting processes. In Proceeding of the 2002 International Symposium, Columbus Ohio, May 2002.

Rynk, R.F., 2004. Odor Management and Abatement Plan. Unpublished Report.

Rynk, R.F., 1992. On Farm Composting Handbook, ed. NRAES, Ithaca, NY.

Rynk, 1994. Almost Mainstream? A Progress Report on Dairy Manure Composting. Proceedings of the Third International Dairy Housing Conference. Orlando, FL. 1994.

Rynk, R.F., 2003a. What it Takes for an Odor Turn-around at a Composting Site. Part I. *BioCycle*, Vol. 44(8).

Rynk, R.F. 2003b. Facing up to Odor Complaints at a Wood Recycling Site. Part II. BioCycle, Vol. 44(9).

Sawyer, C.N. and P.L. McCarty, 1978. Chemistry for Environmental Engineering. McGraw-Hill, Inc., Boston, MA.

Schiffman, S.S., J.M. Walker, P. Dalton, T.S. Lorig, J.H. Raymer, D. Shusterman, and C. M. Williams, 2000. Potential Health Effects of Odor From Animal Operations, Wastewater Treatment and Recycling of Byproducts. Duke University, NC.

Shiffman, S.S., 1998. Livestock Odors: Implications for Human Health and Well-Being., Duke University Medical School, Durham, NC.

Schiffman, S.S., J.J. Classen, B.G. Kermani, and H.T. Nagle. 1995. Application of an electronic nose to differentiate odors from exhaust fans and lagoon. In International Conference on Air Pollution from Agricultural Operators. Kansas City, Missouri. February 7-9, p. 255-261.

Schiffman, S.S., and C.M. Williams, 1999. Evaluation of swine odor control products using human odor panels. In 1999 NC State University Animal Waste Management Symposium.

St. Croix Sensory, Inc., 2005. A Review of the Science and Technology of Odor Measurement. Air Quality Bureau of the Iowa Department of Natural Resources, Des Moines, IA.

Stetter, J.R., and W.R. Penrose, 2001. The Electrochemical Nose. http://electrochem.cwru.edu/ed/encycl/art-n01-nose.htm

Strom, P.F., 1985. Effect of temperature on the bacterial species diversity in thermophilic solid-waste composting. *Applied and Environmental Microbiology* 50: 899-905.

Michigan Composting Coalition, nd. Compost Operator Training Manual.

Tchobanoglous, G., H. Theisen and S. Vigil, 1993. Integrated Solid Waste Management. McGraw-Hill, Inc. New York, NY.

Toffey, W.E., L.H. Hentz, Jr., and M. Haibach, 1995. Control of Odor and VOC Emissions from the Largest Aerated-Static-Pile Biosolids Composting Facility in the U.S. Paper presented at WEFTEC '95. Water Environ. Fed, Miami Beach, FL.

Walker, L.P. and J.M. Gossett, 1999. Controlling Odors and Waste Stabilization in Composting Systems Through Process Design, Analysis and Monitoring. The New York State Energy Research and Development Authority. Albany, NY.

Whatis,com, 2003. Electronic nose. http://whatis.techtarget.com/definition/0,,sid9_gci916181,00.html*)*

Wilber, C., and C. Murray, 1990. Odor Source Evaluation. *BioCycle* 31(3):68-72.

Williams T. O., and F.C. Miller, 1993. Composting Facility Odor Control Using Biofilters: Minimizing Odor Generation. In *Science and Engineering of Composting*. Ohio State University.

Willmink, T.R., and R.G. Diener, *Handbook for Commercial and Municipal composting in West Virginia. (2001).*

Woods End Research Laboratories, 1990. Composting Potato Culls and Potato Processing Wastes. Mount Vernon, ME.